A Rare Opportunity, the Mu2e Experiment

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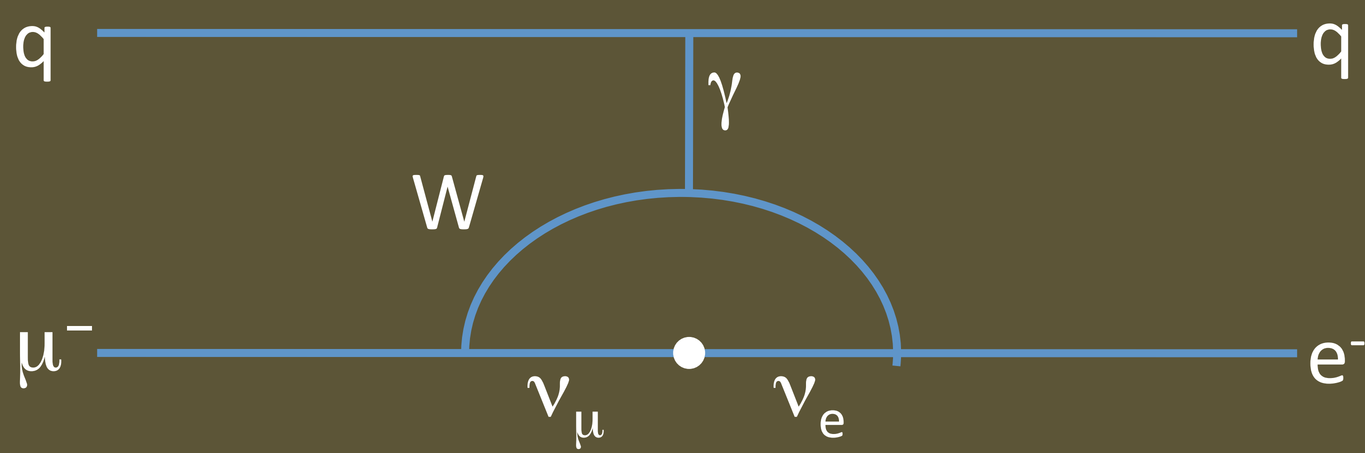
Introduction

- What is Mu2e?
  - A search for Charged-Lepton Flavor Violation via

$$\mu^- N \rightarrow e^- N$$

  - Will use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best
  - Will have *discovery* sensitivity over broad swath of New Physics parameter space

CLFV in the Standard Model



- Strictly speaking, forbidden in the SM
- Even in ν-SM, extremely suppressed
  (rate ~ $\Delta m_\nu^2 / M_W^2 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation CLFV experiments

Flavor Violation

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)

Some CLFV Processes

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

(current limits from the PDG)

- Most promising CLFV measurements use μ

CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

arXiv:0909.5454v2[hep-ph]

- Relative rates model dependent
- Measure several to pin-down theory details

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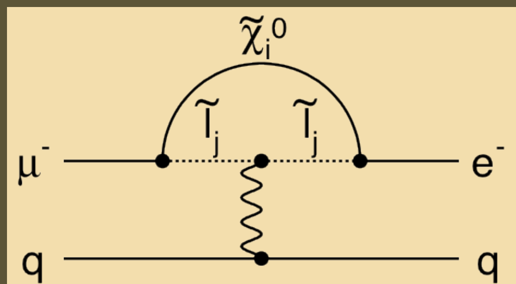
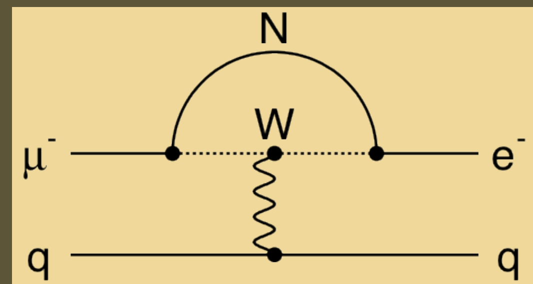
New Physics Contributions to $\mu N \rightarrow eN$

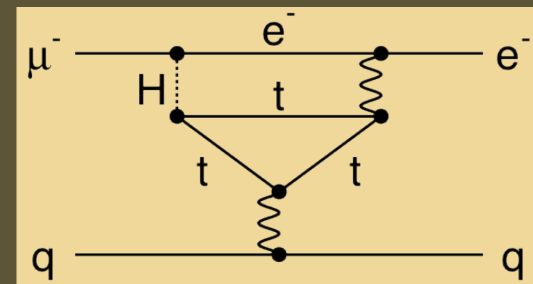
Loops



Supersymmetry

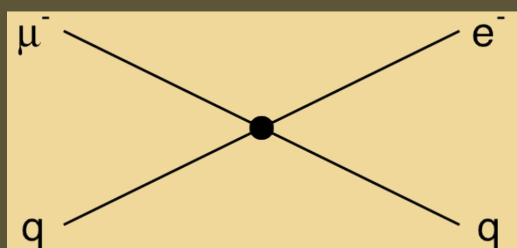


Heavy Neutrinos

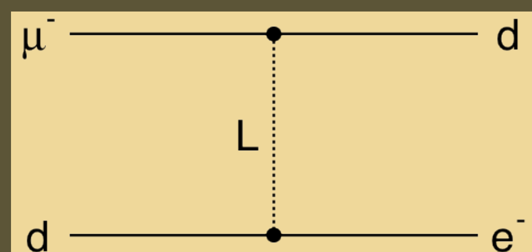


Two Higgs Doublets

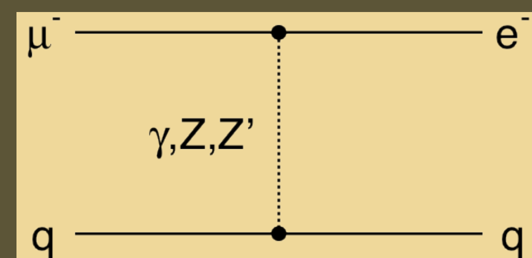
Contact Terms



Compositeness



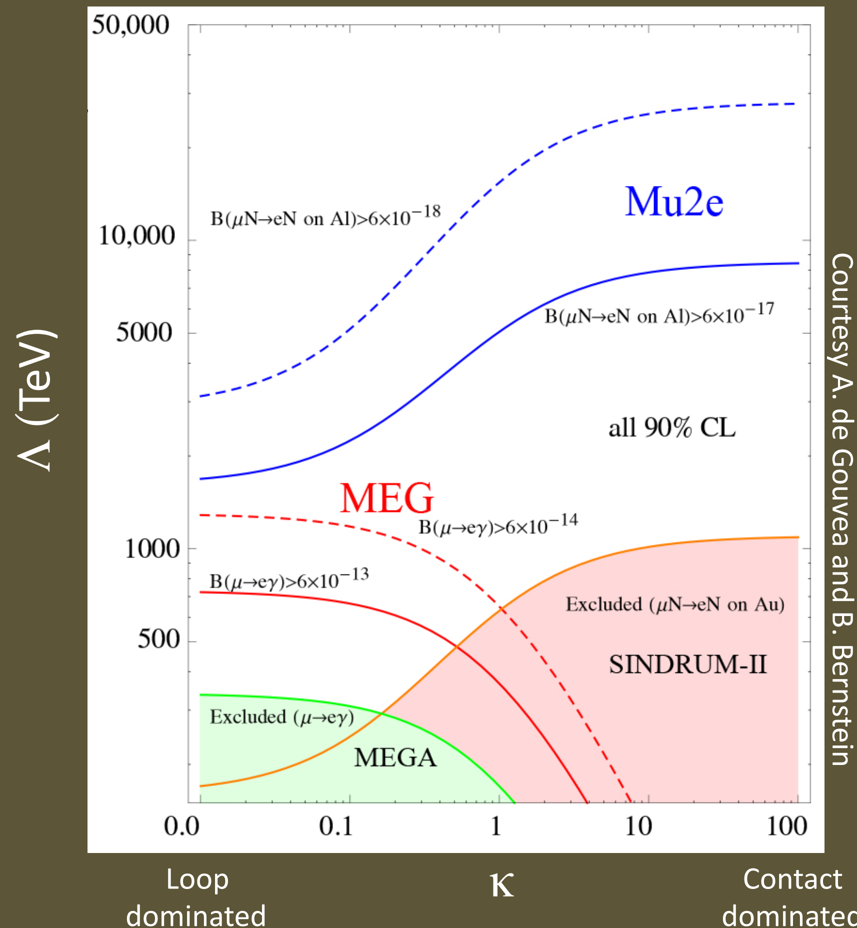
Leptoquarks



New Heavy Bosons /
Anomalous Couplings

$\mu N \rightarrow eN$ sensitive to wide array of New Physics models

Mu2e Sensitivty



- Mu2e Sensitivity best in all scenarios

Mu2e Sensitivity

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3}=0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		SPS 1b		SPS 2		SPS 3		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
BR($\mu \to e\,\gamma$)	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
BR($\mu \to e\,e\,e$)	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
CR($\mu \to e$ in Ti)	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
BR($\tau \to e\,\gamma$)	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
BR($\tau \to e\,e\,e$)	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
BR($\tau \to \mu\,\gamma$)	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
BR($\tau \to \mu\,\mu\,\mu$)	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/SuprB
- All of these will be observable by Mu2e

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

★★★ = Discovery Sensitivity

arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

★★★ = Discovery Sensitivity

arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e in a broader context

- In the 2008 P5 report Mu2e received the highest endorsement:
  - “Mu2e should be pursued in all budget scenarios considered by the panel”
- In 2010 P5 reiterated their support of the 2008 plan and the priorities specified therein.
- In 2013 the Facilities Panel gave Mu2e the highest endorsement:
  - “The science of Mu2e is *Critical* to the DOE OHEP mission and is *Ready to Construct*.”

How does Mu2e work?

Mu2e Concept

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^N important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$

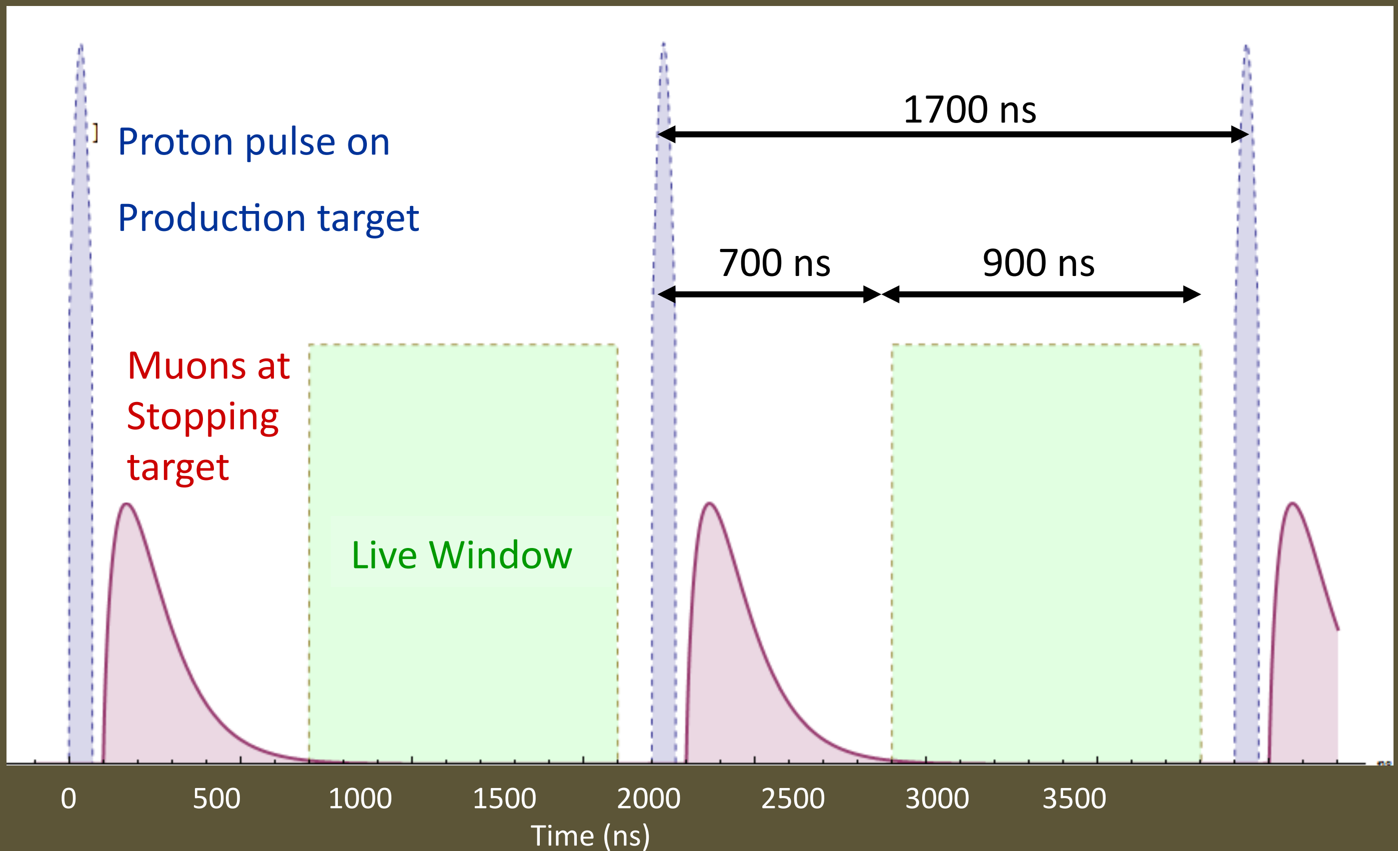
Mu2e Signal

- The process is a coherent one
  - The nucleus is kept intact
- Experimental signature is an electron and nothing else
  - Energy of electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
  - For aluminum: E_e=104.96 MeV
  - Important for discriminating background

Mu2e Sensitivity

- Design goal: single-event-sensitivity ~ 2×10^{-17}
  - Requires about 10^{18} stopped muons
  - Requires about 10^{20} protons on target
  - Requires extreme suppression of backgrounds
- Expected limit: $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
  - Factor 10^{4} improvement
- Discovery sensitivity: all $R_{\mu e} > 1 \times 10^{-16}$
  - Covers broad range of new physics theories

Mu2e Proton Beam



- Mu2e will use a pulsed proton beam and a delayed live gate to suppress prompt backgrounds

Backgrounds

Mu2e Backgrounds

- Intrinsic – scale with no. stopped muons
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)
- Late arriving – scale with no. late protons
  - Radiative pion capture (RPC)
  - μ and π decay-in-flight (DIF)
- Miscellaneous
  - Anti-proton induced
  - Cosmic-ray induced

Mu2e Backgrounds

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.22
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.10
	Cosmic Ray induced	0.05
	Pat. Recognition Errors	<0.01
Total Background		0.41

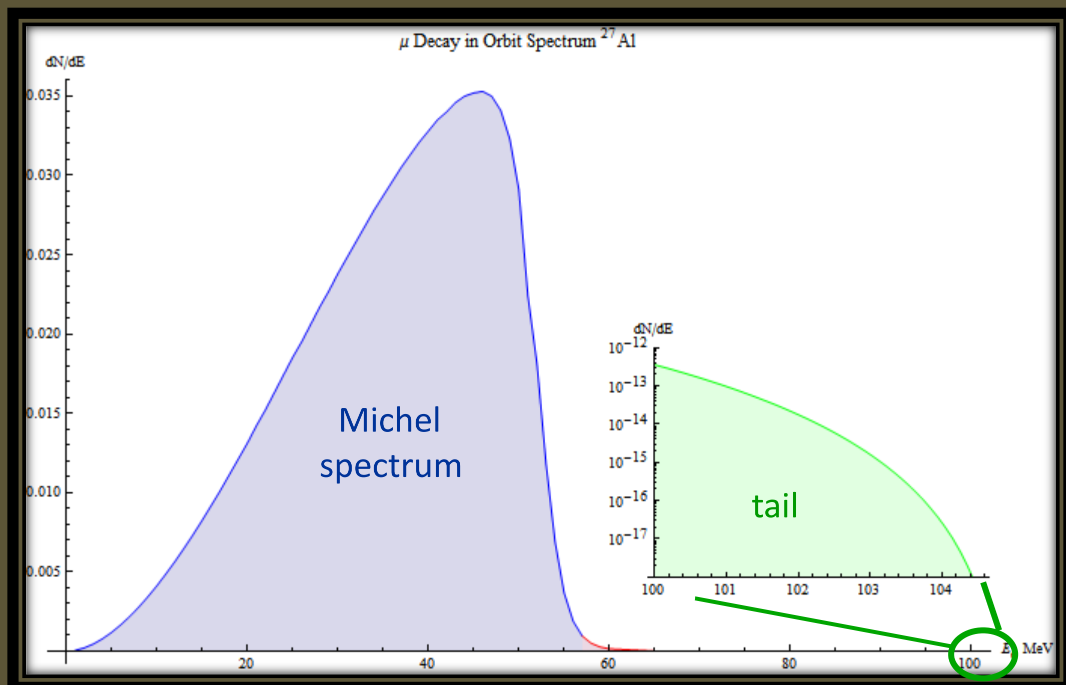
(assuming 6E17 stopped muons in 6E7 s of beam time)

- Designed to be nearly background free

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \rightarrow e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 104.96 MeV
   - Accounts for ~55% of total background



Electron energy in MeV

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

2) Capture on the nucleus:

- For Al. capture fraction is 61%
- Ordinary μ Capture
  - $\mu^- N_Z \dashrightarrow \nu N_{Z-1}$
  - Used for normalization
- Radiative μ capture
  - $\mu^- N_Z \dashrightarrow \nu N_{Z-1} + \gamma$
  - (# Radiative / # Ordinary) ~ 1 / 100,000
  - E_γ kinematic end-point ~102 MeV
  - Asymmetric $\gamma \dashrightarrow e^+e^-$ pair production can yield a background electron

Mu2e Late Arriving Backgrounds

- Backgrounds arising from all the other interactions which occur at the production target
  - Overwhelmingly produce a prompt background when compared to $\tau_\mu^{Al} = 864$ ns
  - Eliminated by defining a signal timing window starting 700 ns after the initial proton pulse
  - Must eliminate out-of-time ("late") protons, which would otherwise generate these backgrounds in time with the signal window

out-of-time protons / in-time protons $< 10^{-10}$

Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z \dashrightarrow N^*_{Z-1} + \gamma$
    - For Al. RπC fraction: 2%
    - E_γ extends out to ~m_π
    - Asymmetric $\gamma \rightarrow e^+e^-$ pair production can yield background electron
  - Beam electrons
    - Originating from upstream π^- and π^0 decays
    - Electrons scatter in stopping target to get into detector acceptance
  - Muon and pion Decay-in-Flight
- Taken together these backgrounds account for ~10% of the total background and scale *linearly* with the number of out-of-time protons

Mu2e Miscellaneous Backgrounds

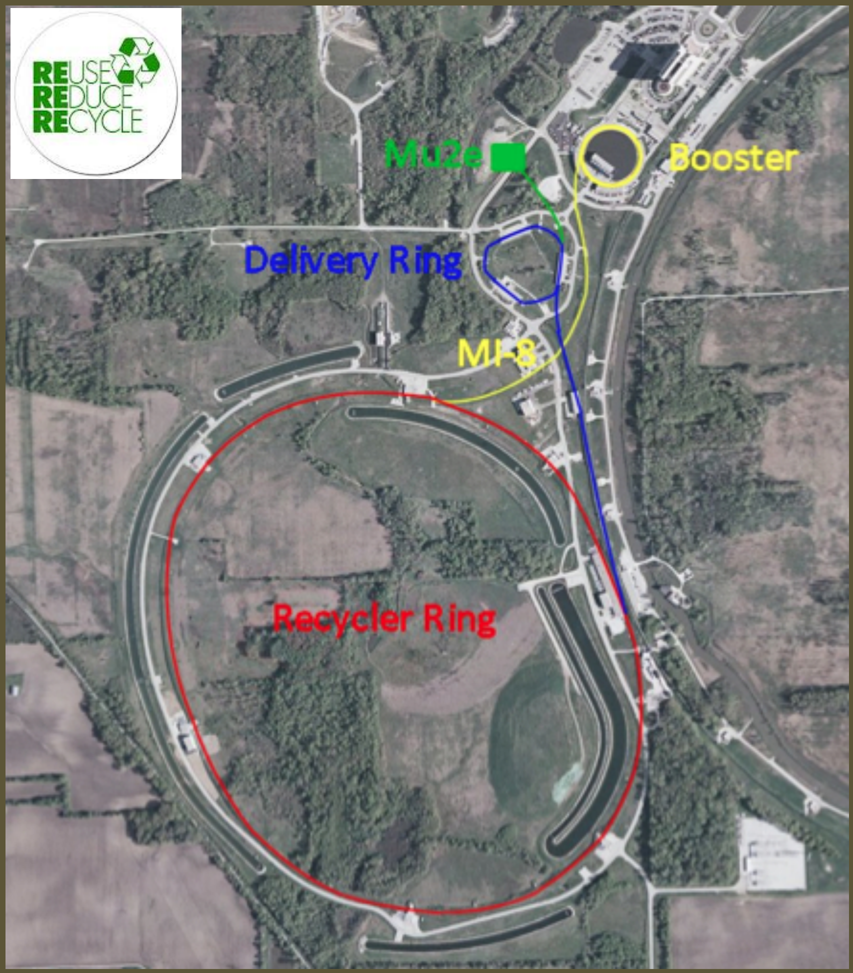
- Several additional miscellaneous sources can contribute background - most importantly:
  - Anti-protons
    - Proton beam is just above pbar production threshold
    - These low momentum pbars wander until they annihilate
    - A thin mylar window in beamline absorbs most if them
    - Annihilations produce high multiplicity final states e.g. π^- can undergo RπC to yield a background electron
  - Cosmic rays
    - Suppressed by passive and active shielding
    - μ DIF or interactions in the detector material can give an e^- or γ that yield a background electron
    - Background listed assumes veto efficiency of 99.99%

Keys to Mu2e Success

- Pulsed proton beam
  - Narrow proton pulses (< +/- 125 ns)
  - Very few out-of-time protons (< 10^{-10})
- Avoid trapping particles… B-field requirements
  - Further mitigates beam-related backgrounds
- High CR veto efficiency (>99.99%)
- Excellent momentum resolution (<200 keV core)
- Thin anti-proton annihilation window

The Mu2e Beamlines

The Mu2e Proton Beam



- Mu2e begins by using protons to produce pions
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Mu2e can (and will) run simultaneously with NOvA.

The Mu2e Proton Beam

Item	Value	Units
Number of spills per MI cycle	8	
Number of protons per micro-pulse	31	Mp
Maximum Delivery Ring Beam Intensity	1.0	Tp
Instantaneous spill rate	18.5	Tp/sec
Average spill rate	6.0	Tp/sec
Duty Factor	32	%
Duration of spill	54	msec
Spill On Time per MI cycle	497	msec
Spill Off Time per MI cycle	836	msec
Time Gap between 1st set of 4 and 2nd set of 4 spills	36	msec
Time Gap between spills	5	msec
Pulse-to-pulse intensity variation[f]	±50	%

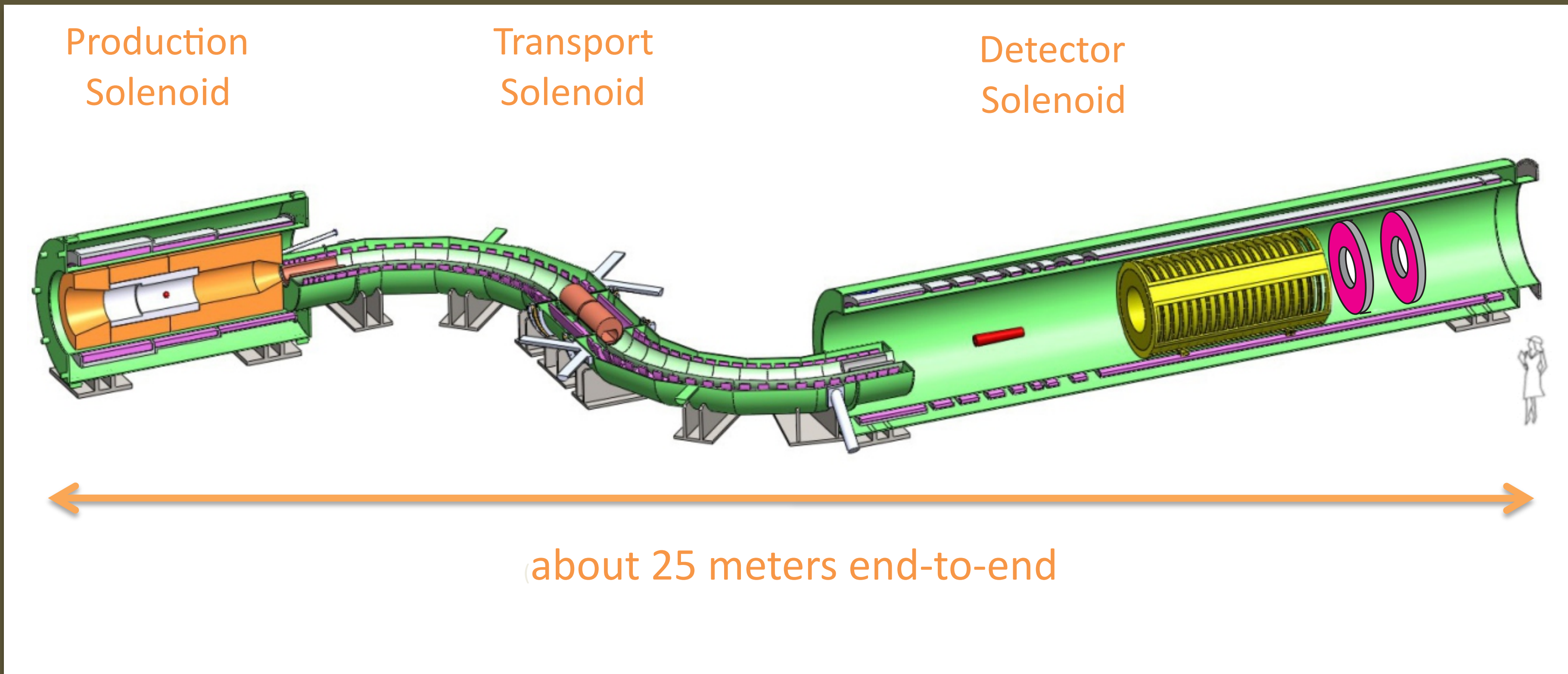
Table 5.2. Delivery Ring Spill Parameters

- Mu2e will use 8kW of 8 GeV proton beam

Mitigating out-of-time protons

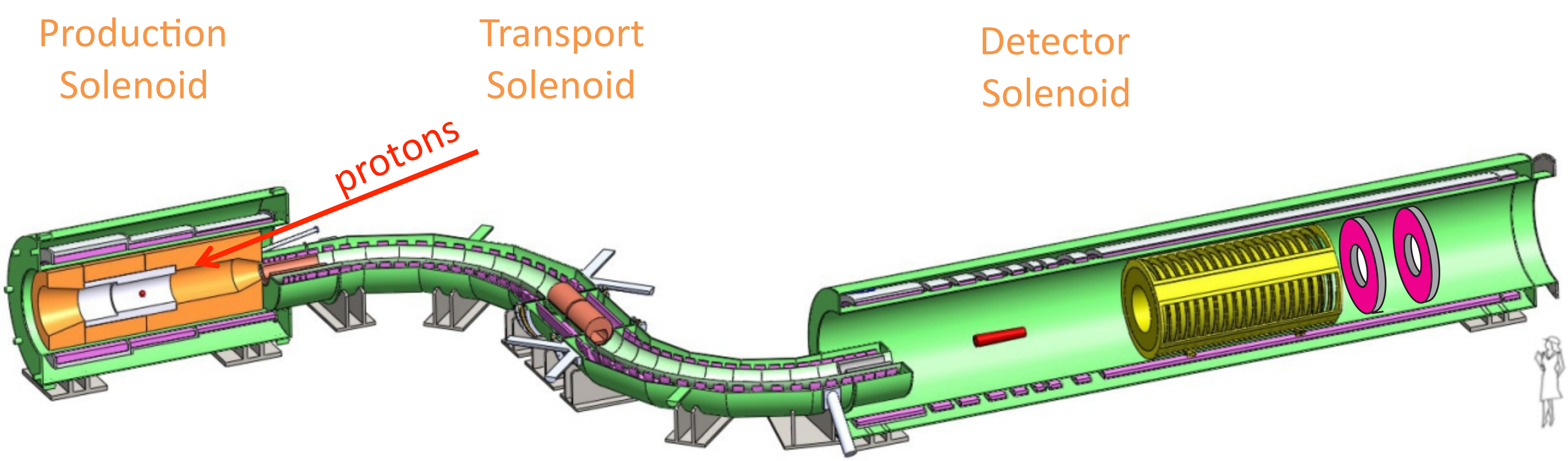
- The RF structure of the Recycler provides some "intrinsic" extinction:
  - Extinction (Intrinsic) = few 10^{-5}
- A custom-made AC dipole placed just upstream of the production target provides additional "external" extinction:
  - Extinction (AC dipole) = $10^{-6} – 10^{-7}$
- Together they provide a total extinction:
  - Extinction (Total) = few $10^{-11} – 10^{-12}$

Mu2e Experimental Apparatus



- Consists of 3 solenoid systems

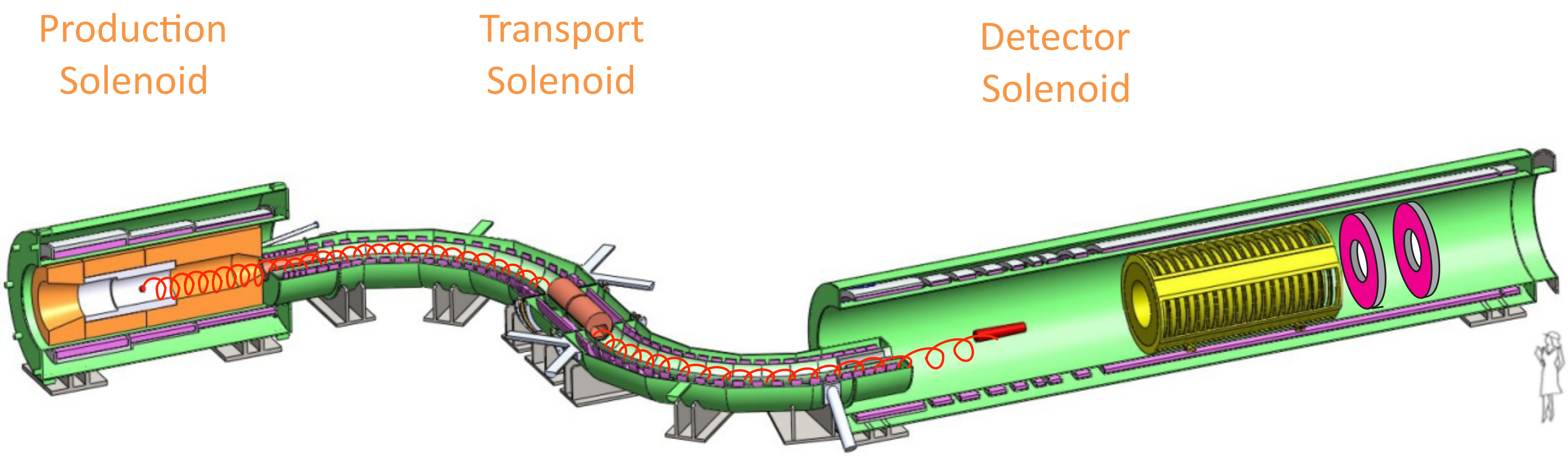
Mu2e Experimental Apparatus



Production Solenoid:
8 GeV protons interact with a tungsten target to produce μ- (from π- decay)

- Consists of 3 solenoid systems

Mu2e Experimental Apparatus



Transport Solenoid:
Captures π- and subsequent μ-; momentum- and sign-selects beam

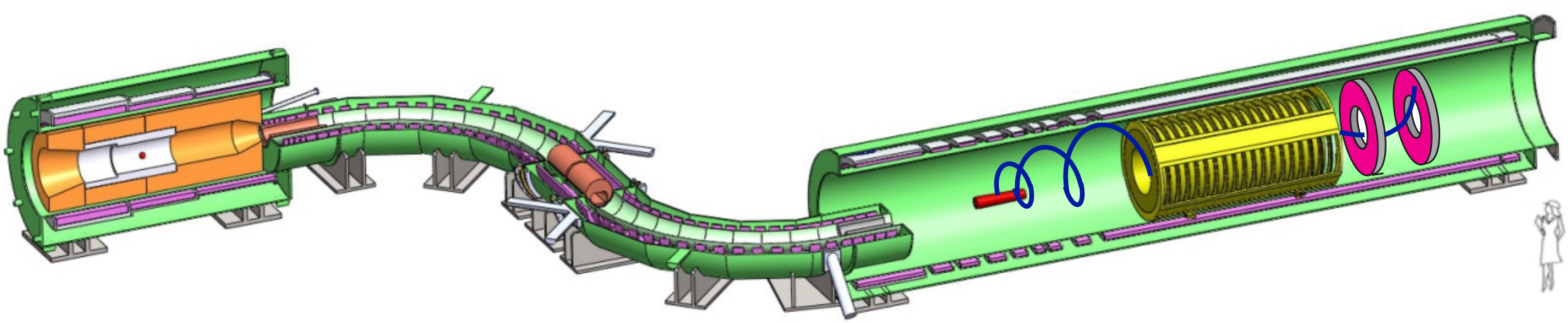
- Consists of 3 solenoid systems

Mu2e Experimental Apparatus

Production Solenoid

Transport Solenoid

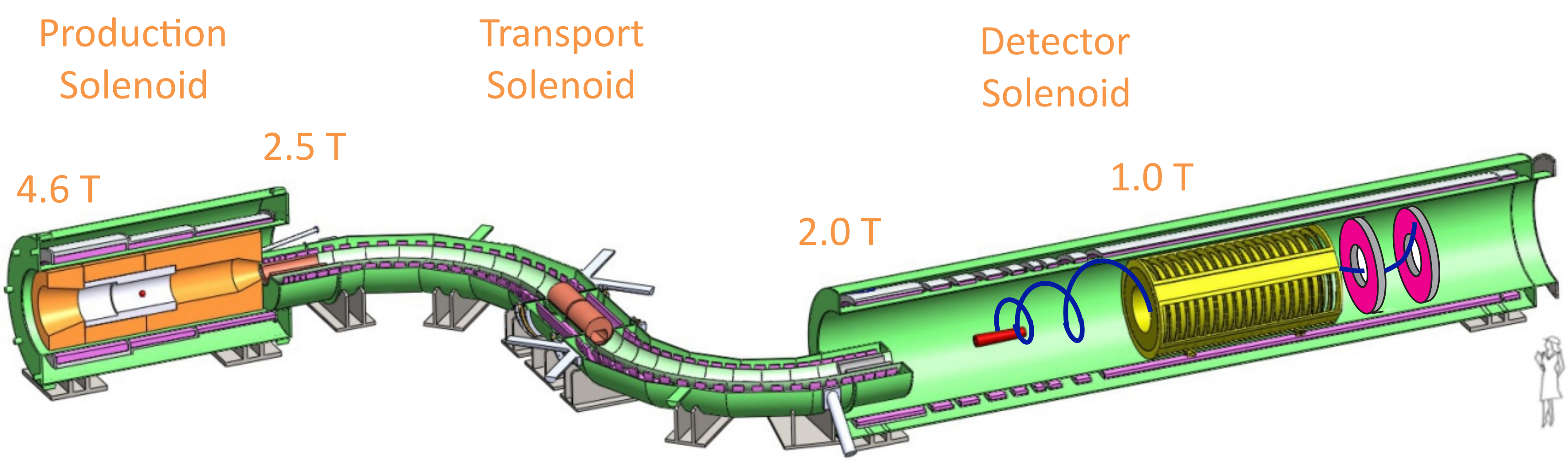
Detector Solenoid



Detector Solenoid:
Upstream – Al. stopping target, Downstream – tracker, calorimeter
(not shown – cosmic ray veto system, extinction monitor, target monitor)

- Consists of 3 solenoid systems

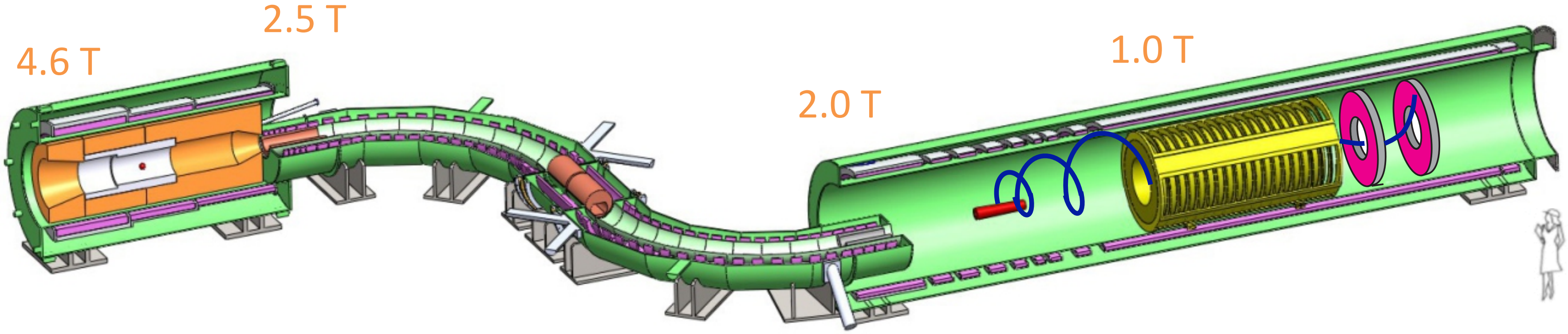
Mu2e Experimental Apparatus



Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

- Consists of 3 solenoid systems

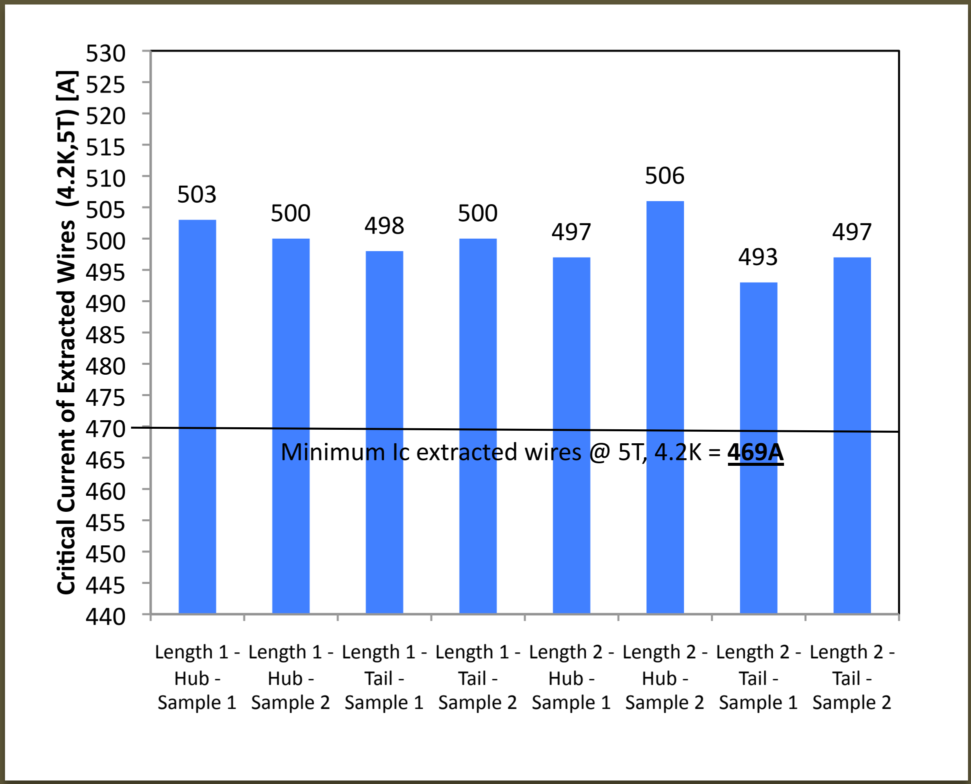
Mu2e Experimental Apparatus

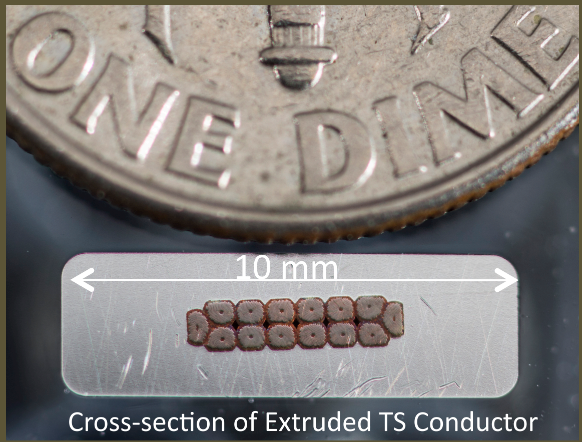


Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

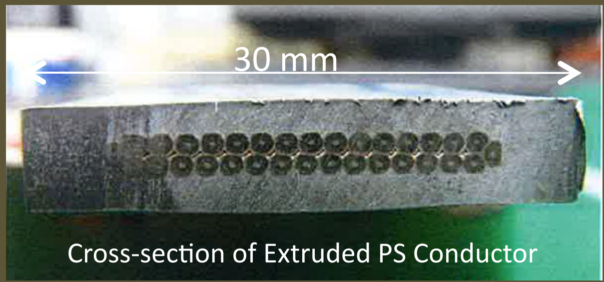
- Derived from MELC concept originated by Lobashev and Djilkibaev

Mu2e Conductor R&D





Cross-section of Extruded TS Conductor



Cross-section of Extruded PS Conductor

- Have nearly completed conductor R&D
  - TS and DS conductor demonstrated, ready to go
  - PS converging, aim to finish R&D this spring/summer

Mu2e Solenoid Summary

	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	50	11
Conductor (km)	10	44	15
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS will be built in industry
- TS will be assembled at Fermilab

Mu2e Solenoid Summary

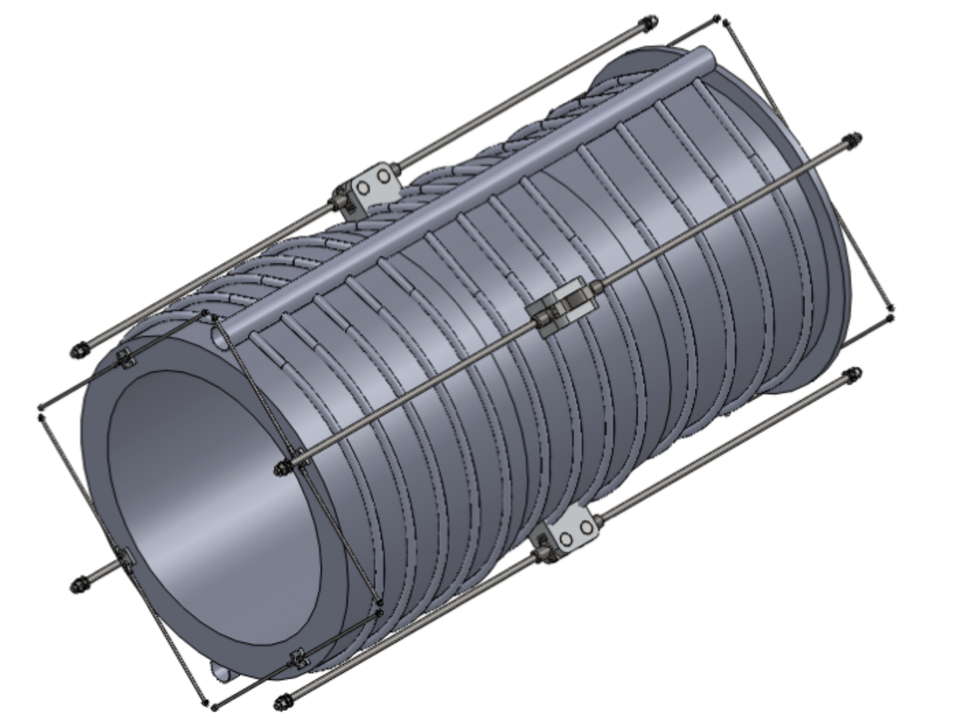


Figure 7.6. Coil cold mass with cooling tubes and support structure.

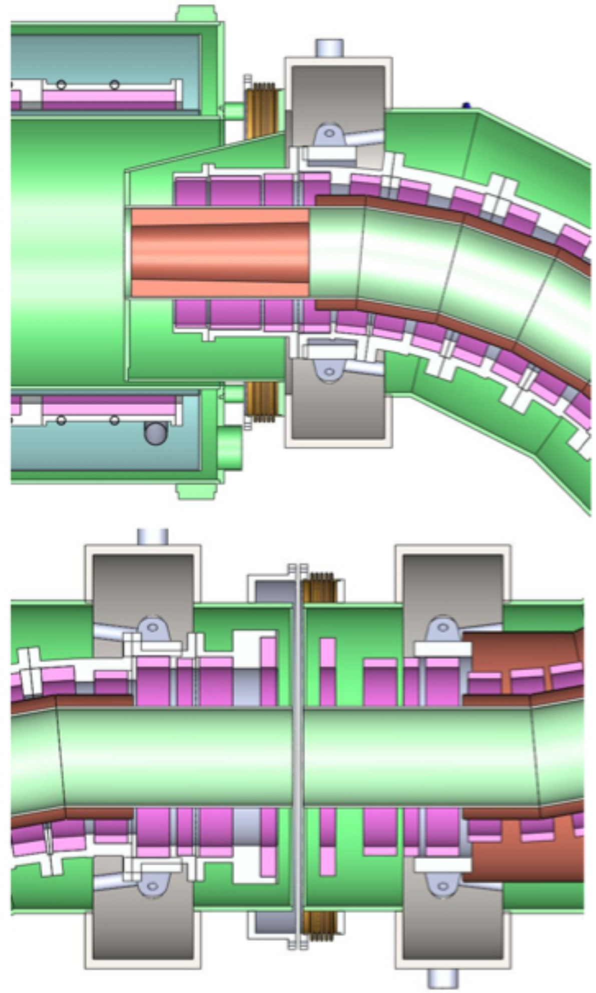


Figure 7.25. TSu Cryostat Interfaces. Top: TSu-PS interface; Bottom; TSu-TSd interface.

- Designs are well advanced.

Mu2e Solenoid Summary

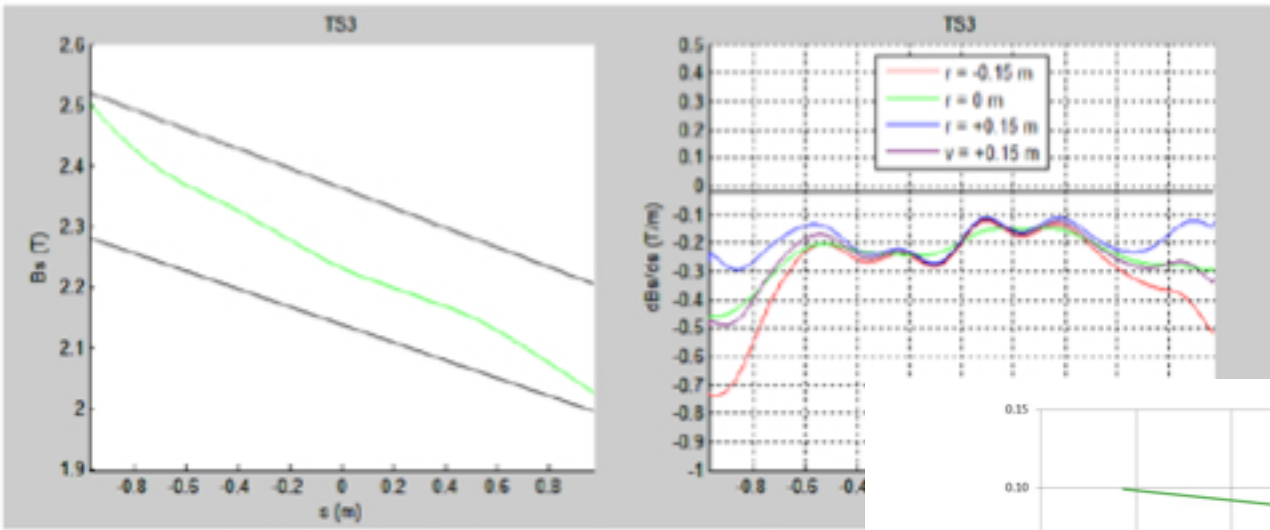


Figure 7.28. Axial field distribution at the center of TS3 (le
(right).

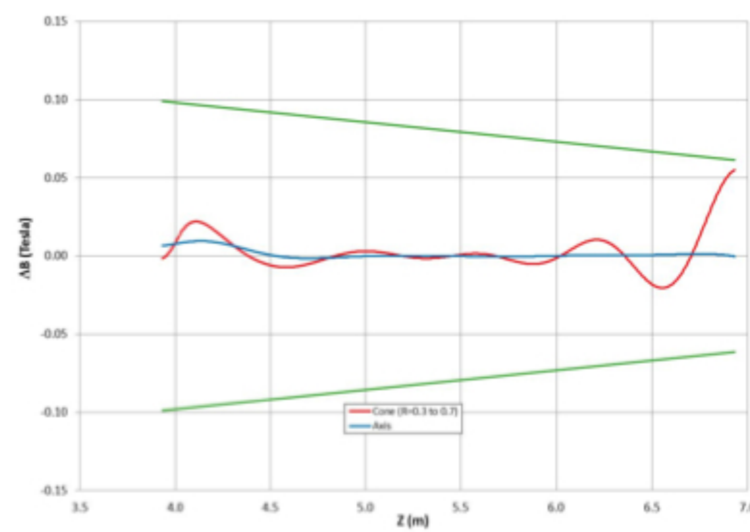
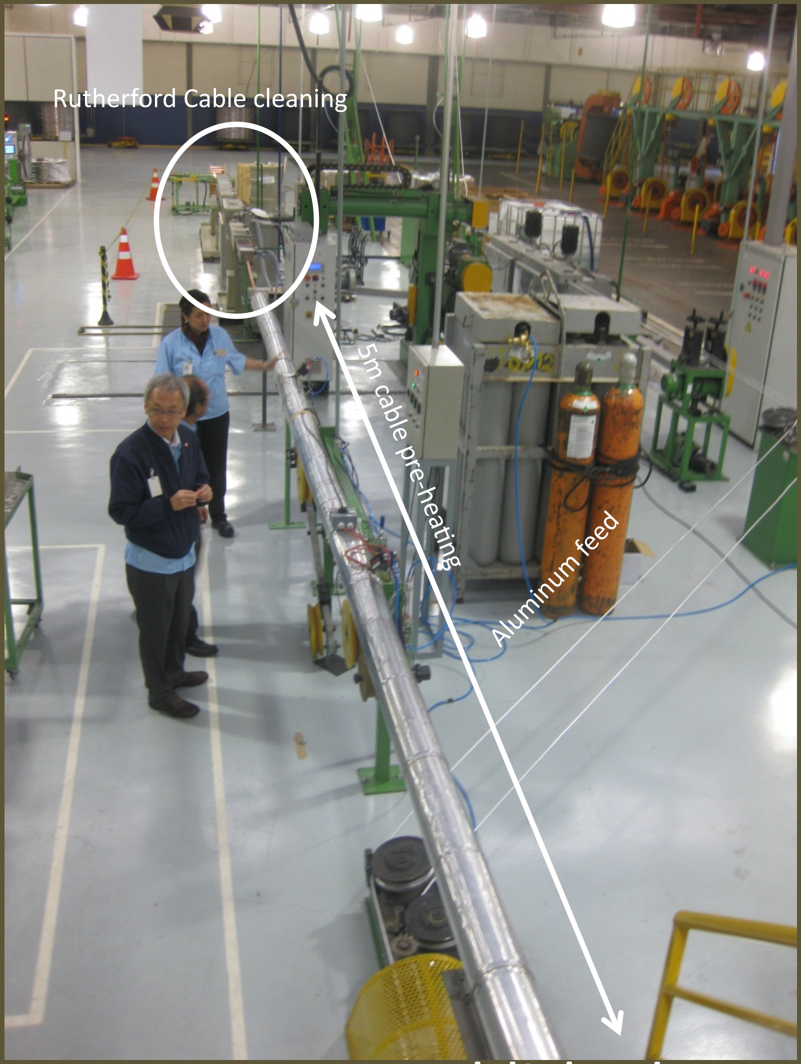
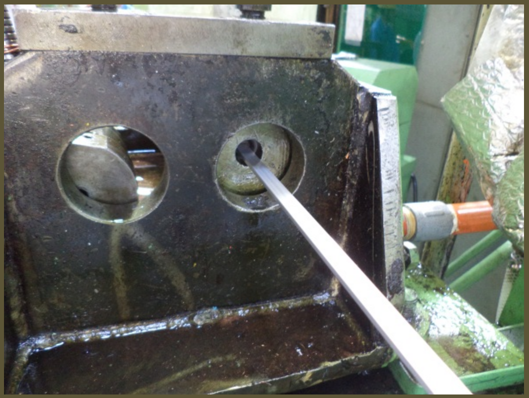


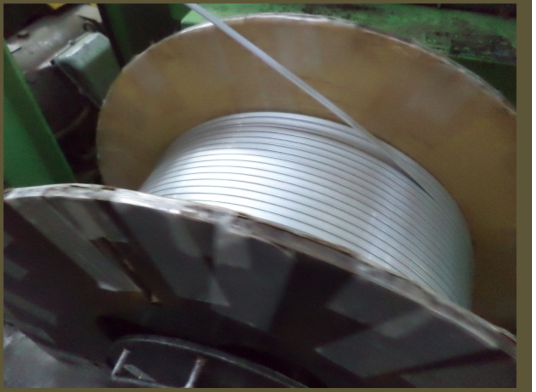
Figure 7.39. Comparison of the magnetic field with the field requirements in the DS gradient section (DS1 Gradient). Field requirements from Table 7.2 are shown in green. ΔB is relative to uniform gradient of -0.25 T/m and a field value of 1. 5 T at the stopping target on axis (blue); on a radial cone from 0.3m to 0.7 m starting at the upstream end of DS1 section (red).

- Designs meet field specs (including fabrication and design tolerances).

Mu2e Conductor R&D







- Have established a good relationship with the vendors

Some Mu2e numbers

- Every 1 second Mu2e will
  - Send 7,000,000,000,000 protons to the Production Solenoid
  - Send 26,000,000,000 μs through the Transport Solenoid
  - Stop 13,000,000,000, μs in the Detector Solenoid
- By the time Mu2e is done…

Total number of stopped muons

1,000,000,000,000,000,000,000

Some Perspective

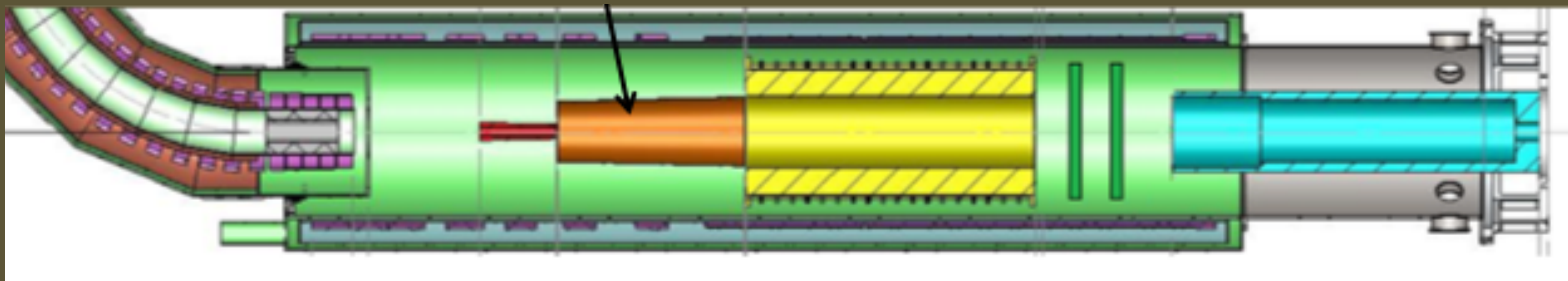
1,000,000,000,000,000,000

= number of stopped Mu2e muons

= number of grains of sand on earth's beaches

The Mu2e Detectors

The Mu2e Detector



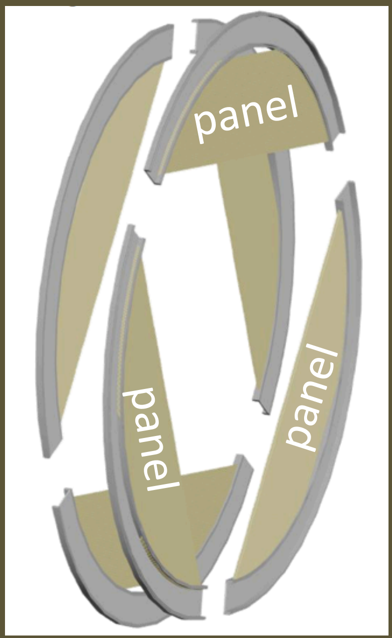
- I am going to focus on the principle elements:
  - Tracker, Calorimeter, Cosmic-Ray Veto

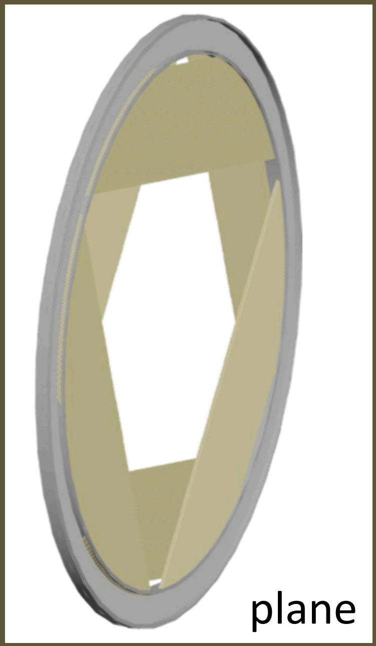
The Mu2e Tracker

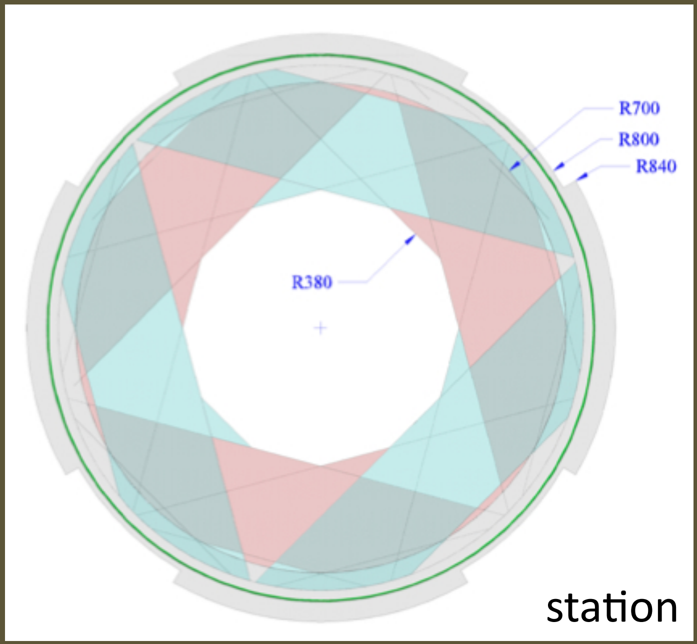
- Will employ straw technology
  - Low mass
  - Can reliably operate in vacuum
  - Robust against single-wire failures

- 5 mm diameter straw
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V

The Mu2e Tracker



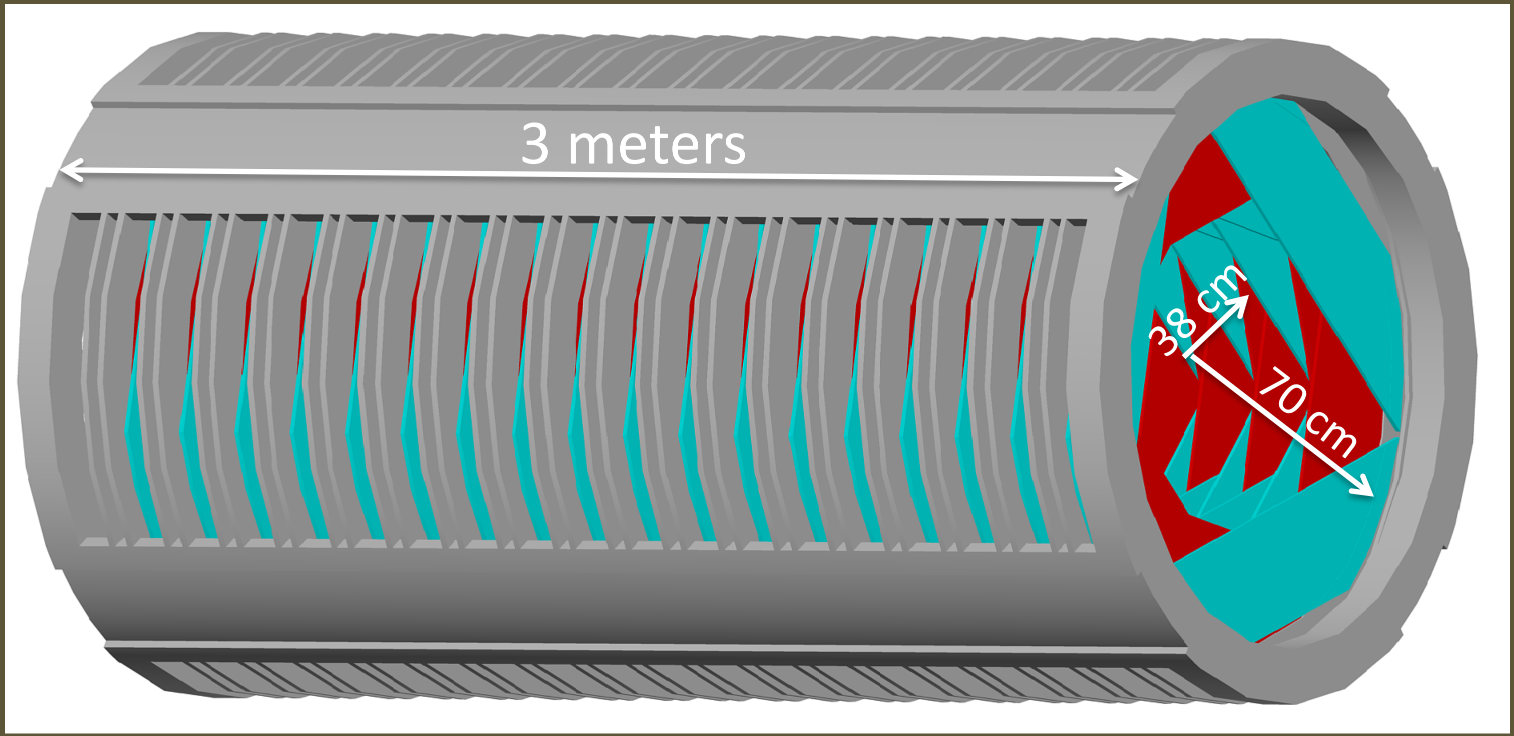




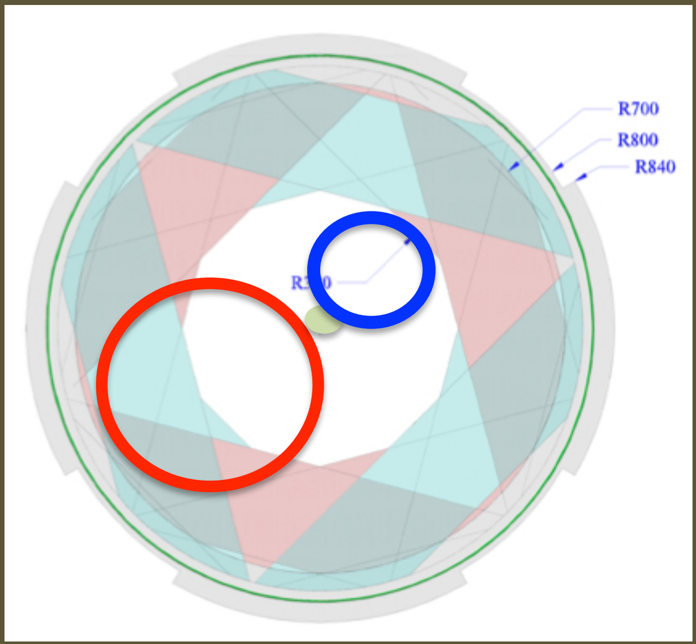
- Self-supporting “panel” consists of 100 straws
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- 21600 straws total

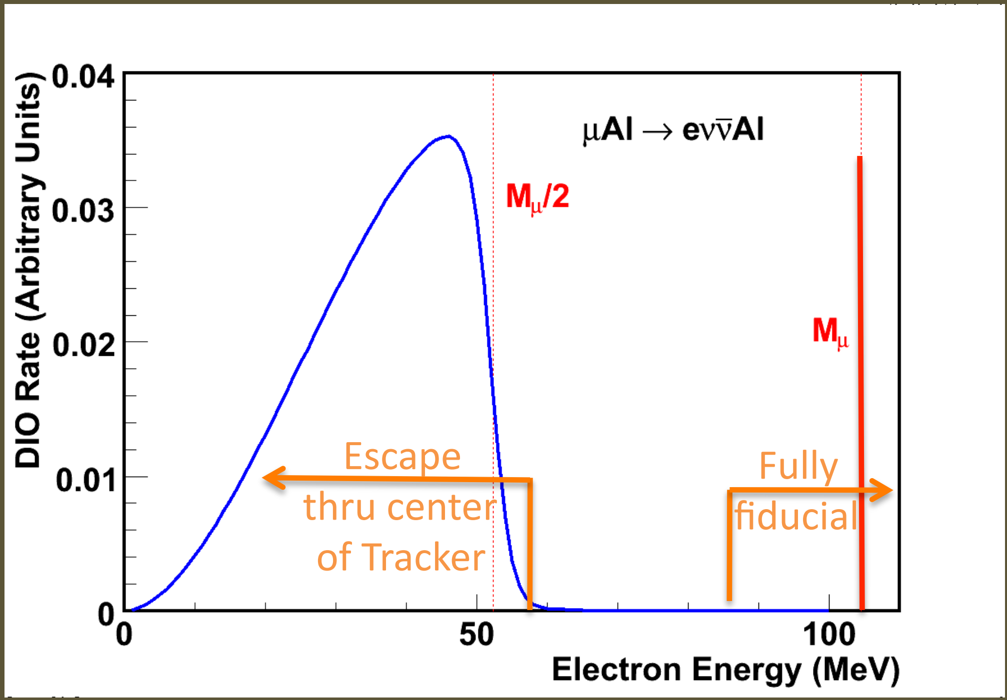
The Mu2e Tracker

- 18 “stations” with straws transverse to beam
- Naturally moves readout and support to large radii, out of active volume



The Mu2e Tracker





- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

Mu2e Track Reconstruction

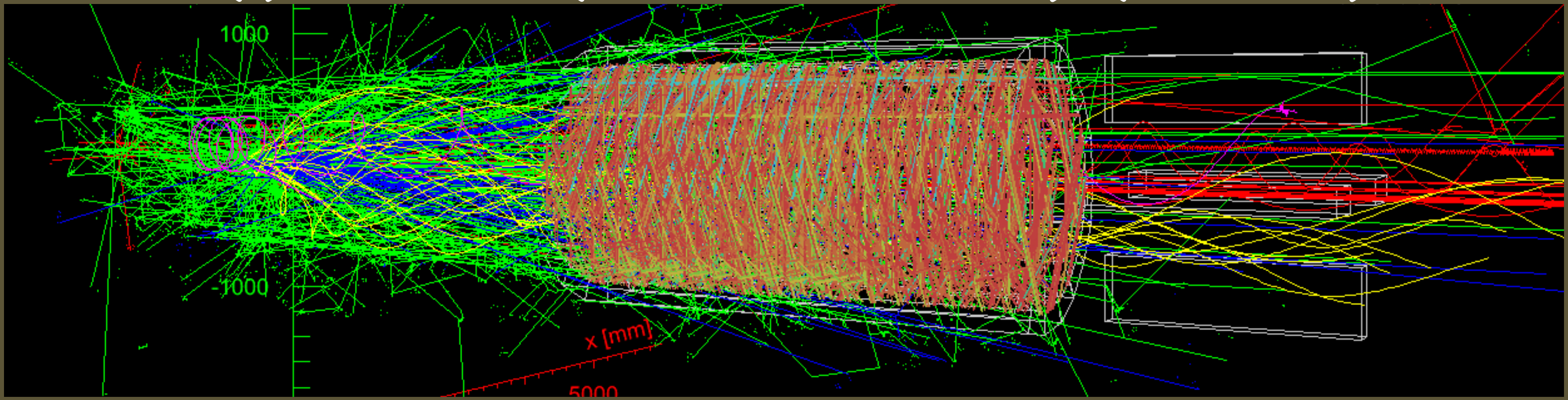
- Straw-hit rates
  - From beam flash (0-300 ns): ~1000 kHz/cm^2
    - Need to survive this, but won't collect data
  - Later, near live window (>500 ns)
    - Peak ~ 20 kHz/cm^2 (inner straws)
    - Average ~ 10 kHz/cm^2 (over all straws)

Mu2e Pattern Recognition

Stopping Target

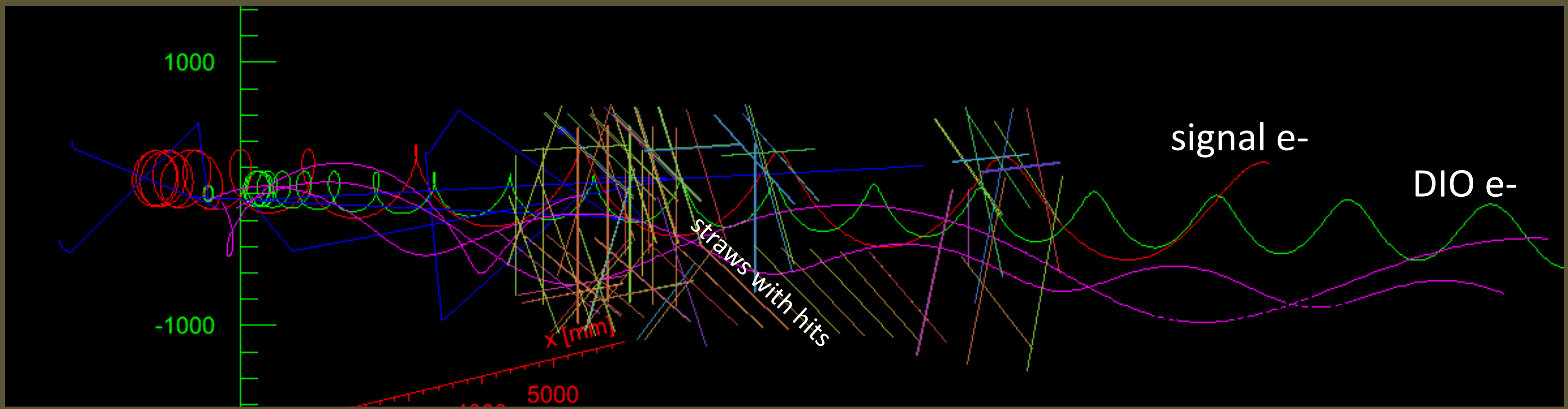
Straw Tracker

Crystal Calorimeter



- A signal electron together with all the other "stuff" occurring simultaneously integrated over 500-1695 ns window

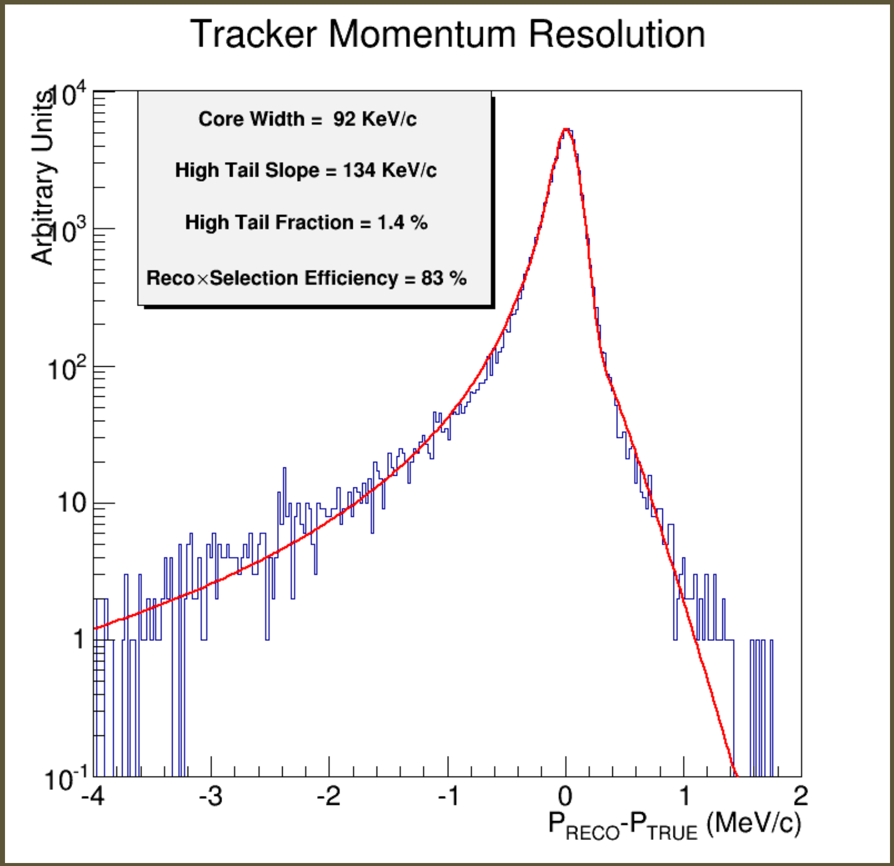
Mu2e Pattern Recognition



(particles with hits within +/-50 ns of signal electron t_{mean})

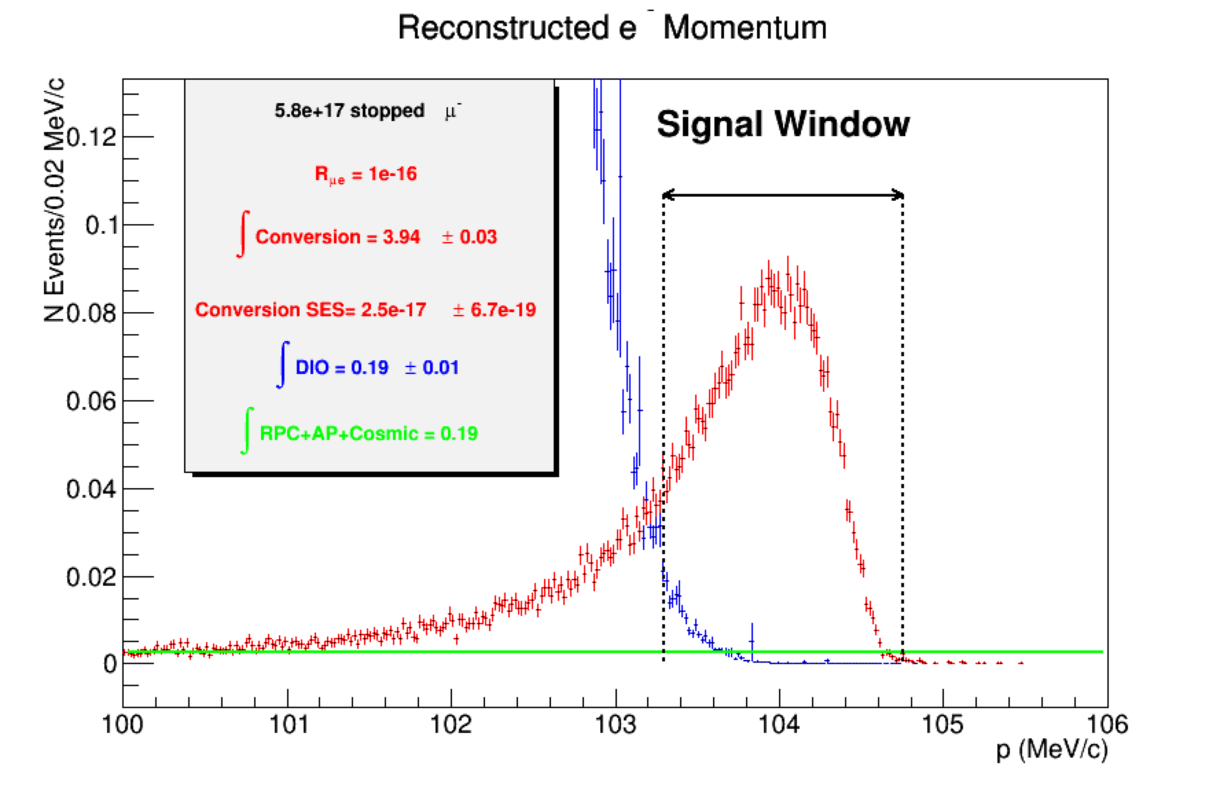
- We use timing information to look in +/- 50 ns windows – significant reduction in occupancy and significant simplification for Patt. Rec.

Mu2e Spectrometer Performance



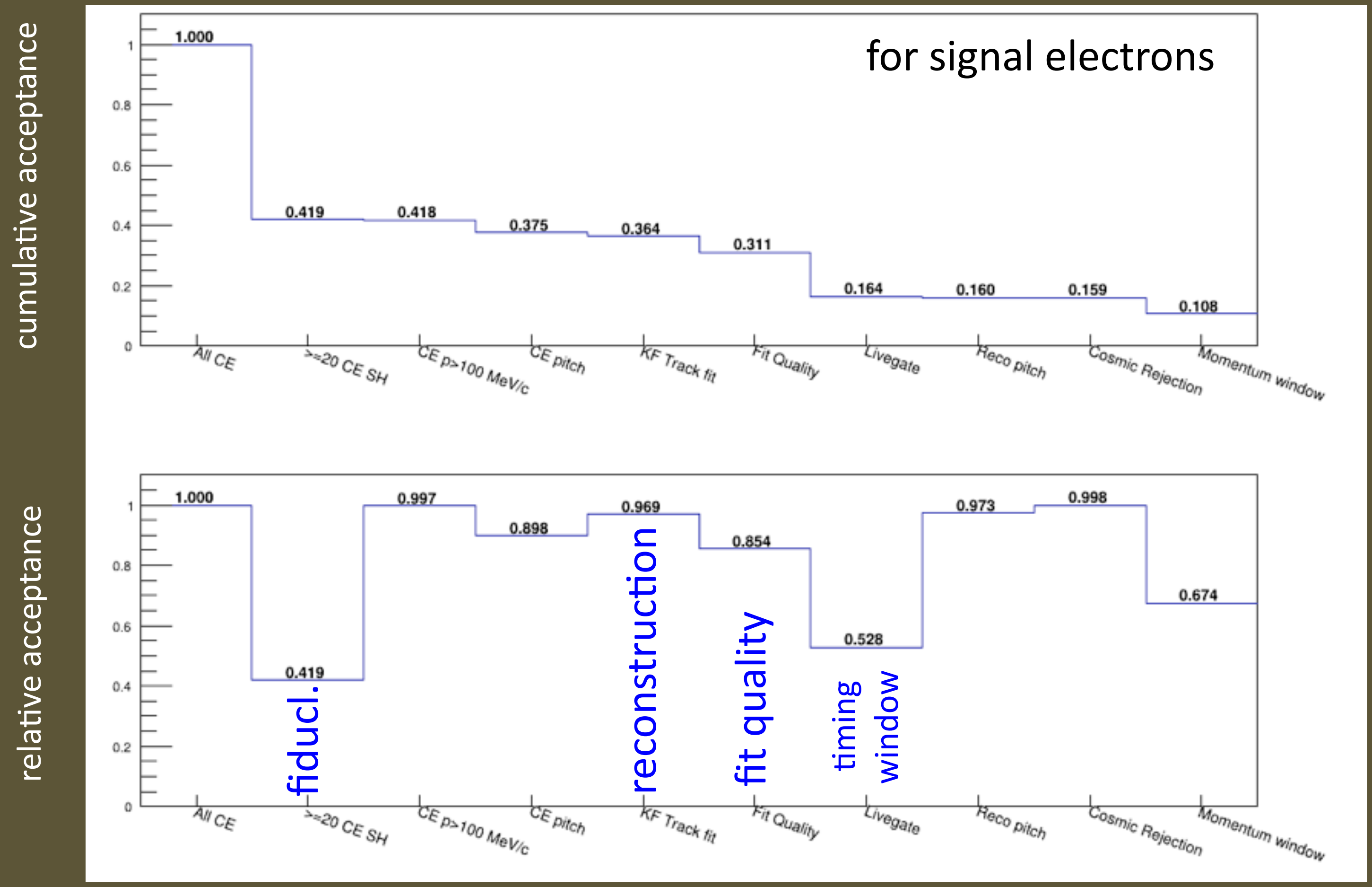
- Performance well within physics requirements

After all analysis requirements



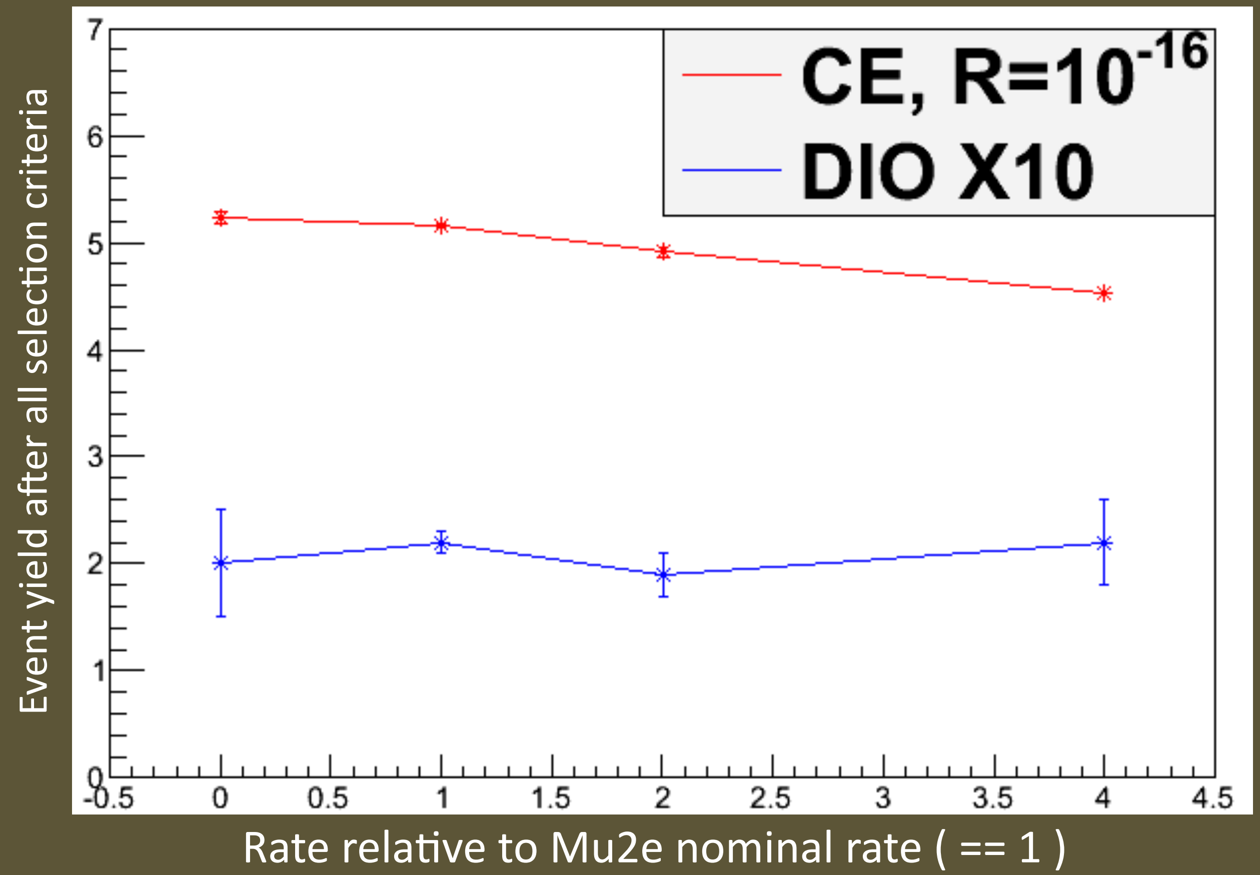
- Single-event-sensitivity = 2.5×10^{-17}
  - Total background < 0.5 events

Reconstruction and Selection Efficiencies



- Inefficiency dominated by geometric acceptance and delayed signal-timing window

Mu2e Performance



- Robust against increases in rate

Mu2e Calorimeter

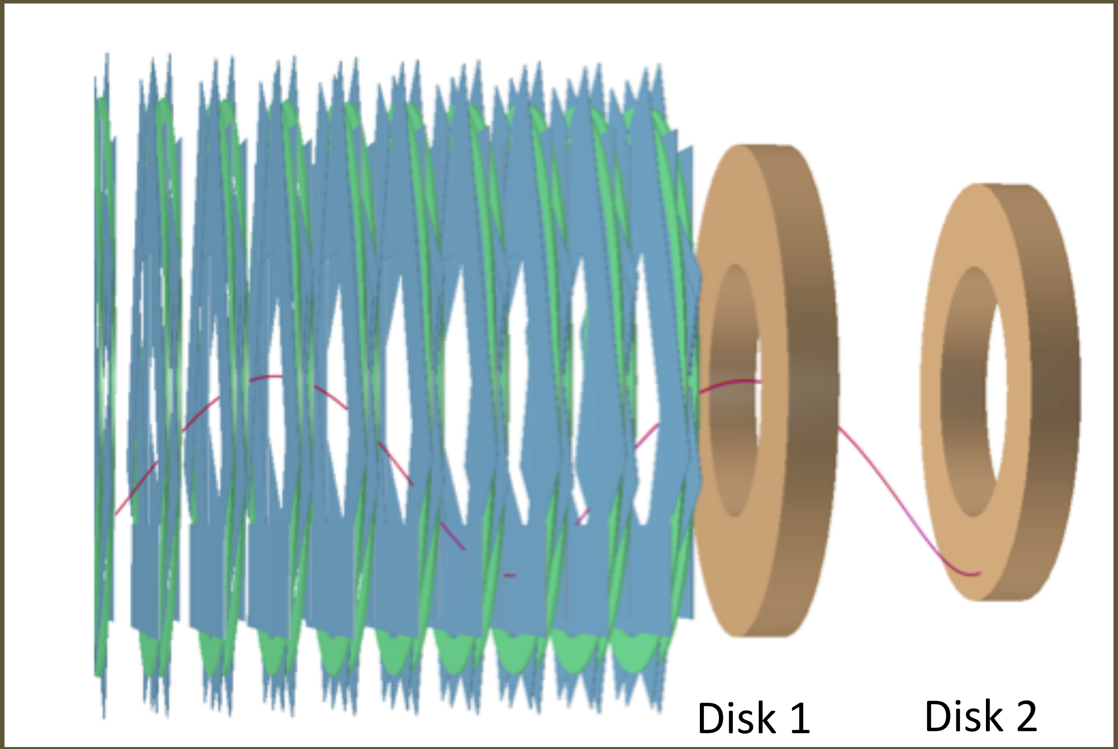
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing and energy resolution

Mu2e Calorimeter

- Baseline design : Barrium Flouride (BaF_2)
  - Radiation hard, very fast, non-hygroscopic

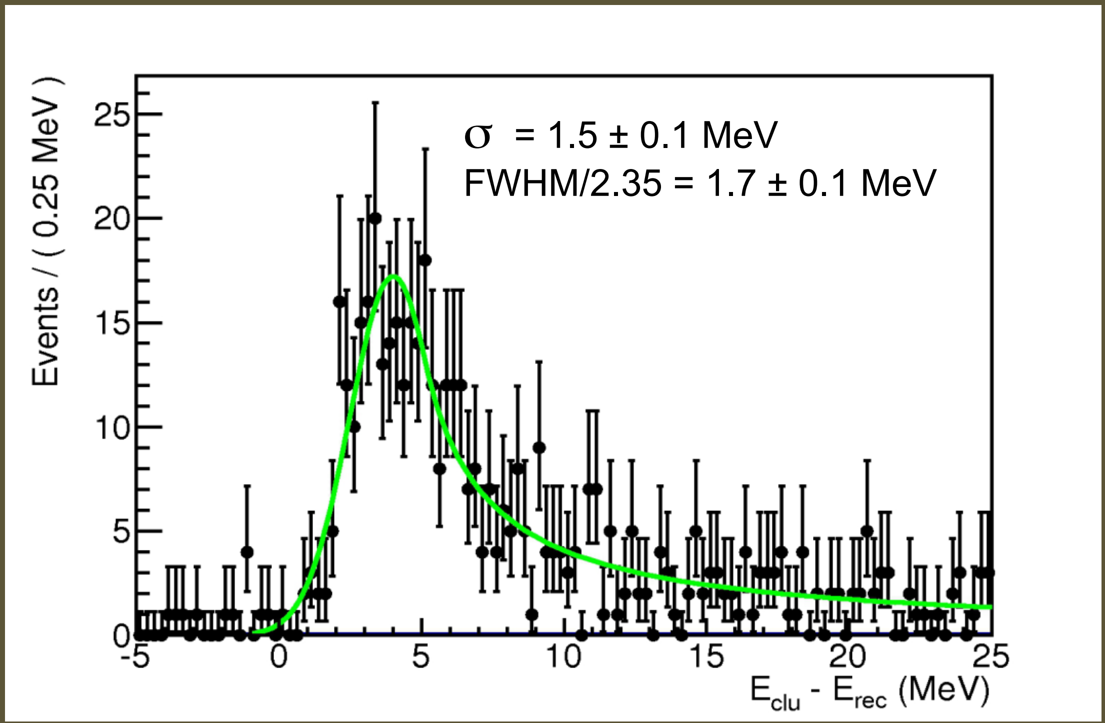
	BaF_2
Density (g/cm3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.9)% / deg-C

Mu2e Calorimeter



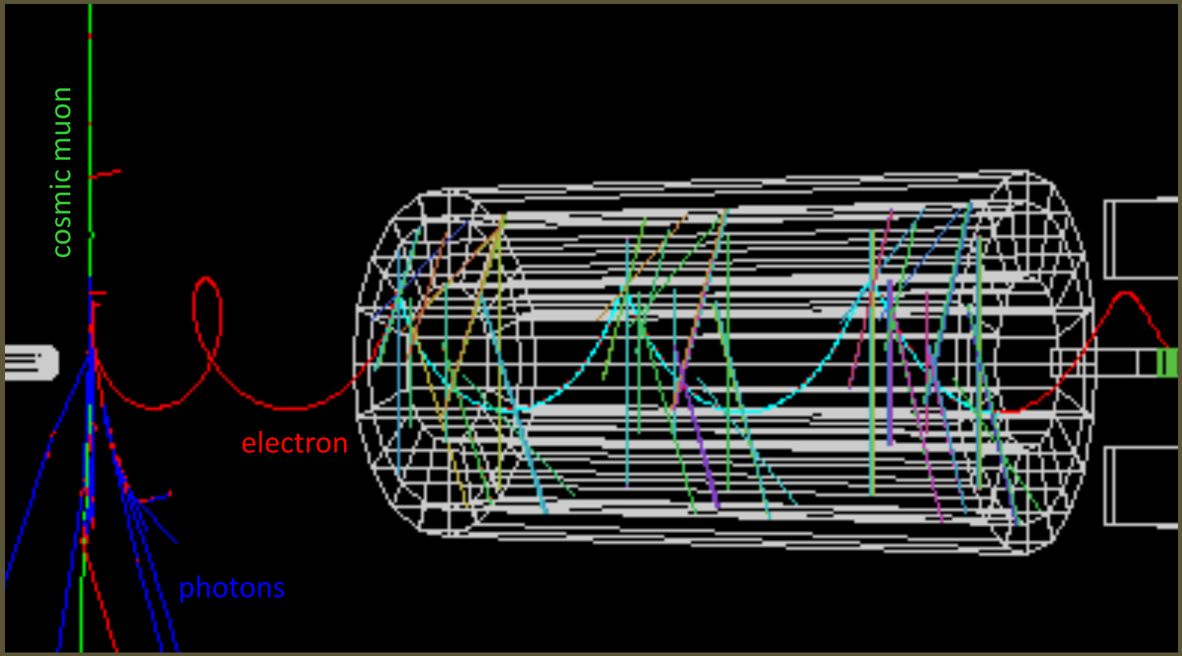
- Will employ 2 disks (radius = 36-70 cm)
- ~2000 crystals with hexagonal cross-section
  - ~3 cm diameter, ~20 cm long (10 X_0)
- Two photo-sensors/crystal on back (APDs or SiPMs)

Mu2e Calorimeter



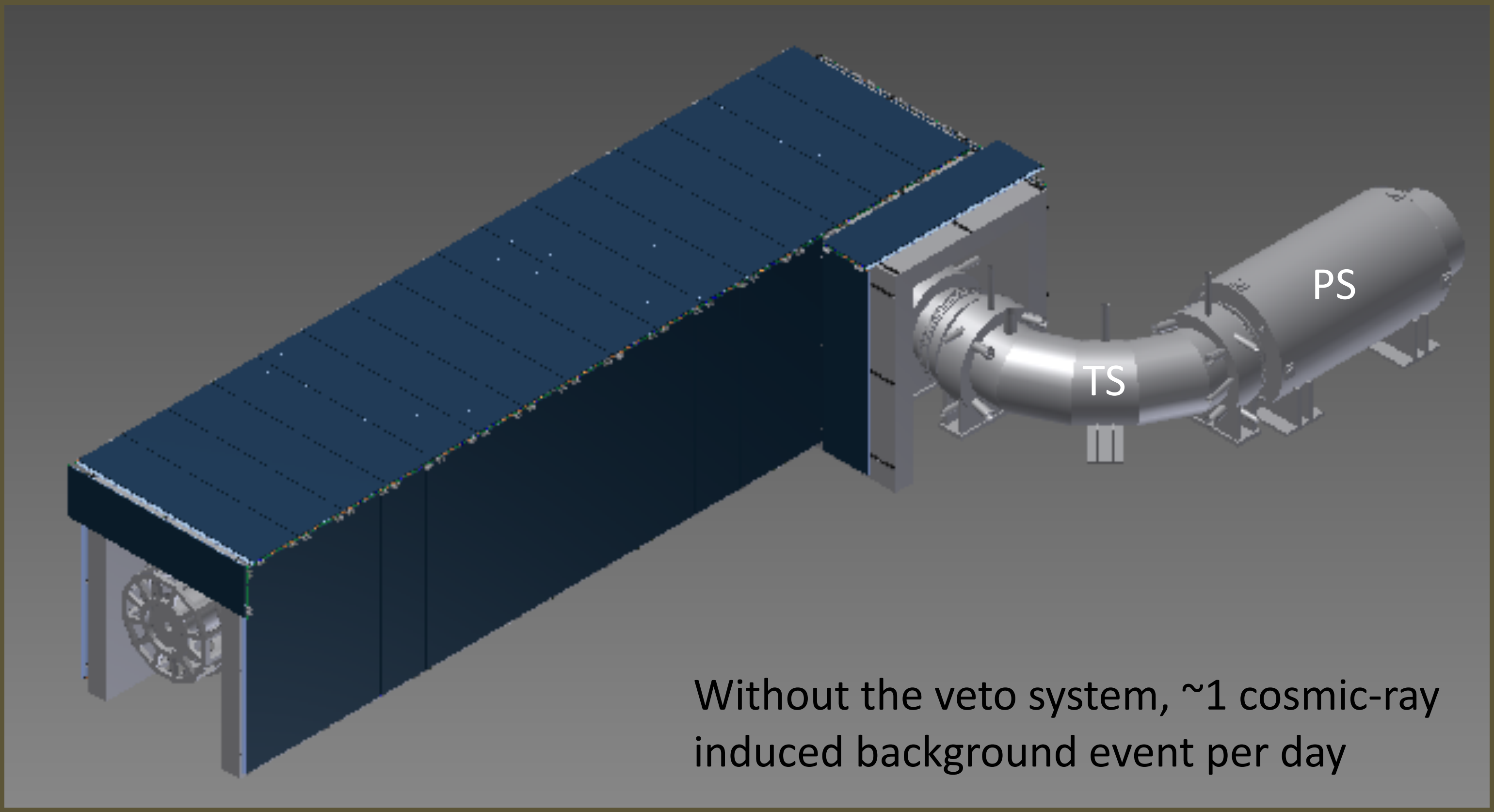
- With 40 ns hit separation, expect to achieve an energy resolution <5% for 105 MeV electrons
  - Performance a weak function of rate in relevant range

Mu2e Cosmic-Ray Veto



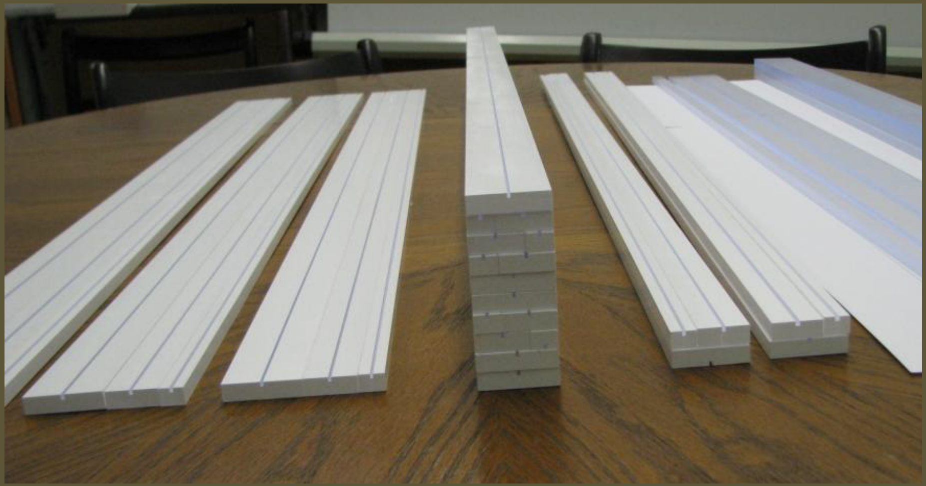
- Cosmic μ can generate background events via decay, scattering, or material interactions

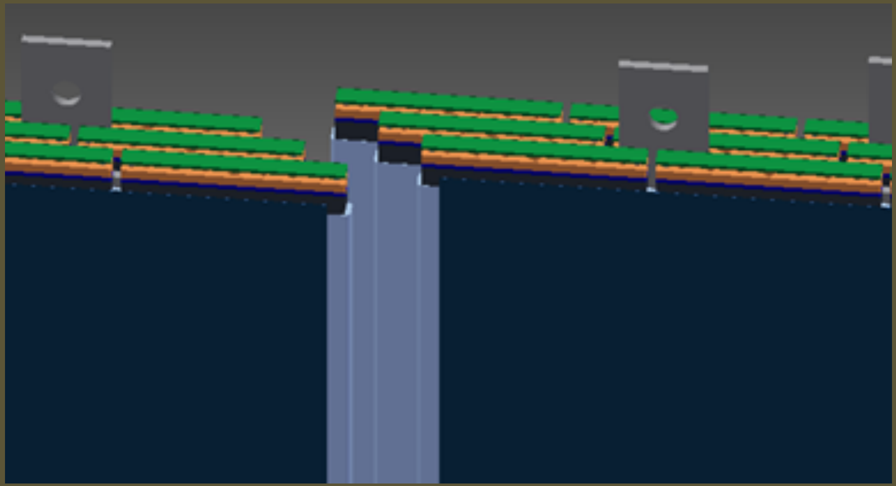
Mu2e Cosmic-Ray Veto



- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto



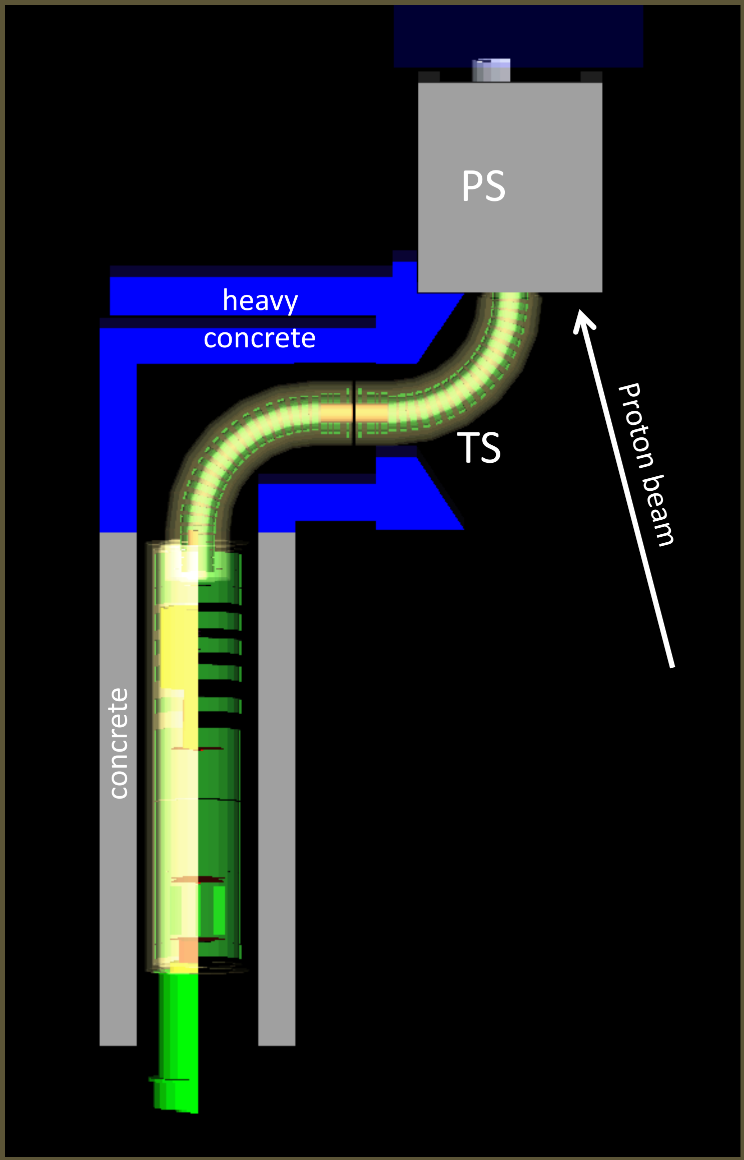


- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

Mu2e Neutron Shielding

- Several copious sources of neutrons
  - Production target, stopping target, collimators
- Lots of neutrons and subsequent photons (from n- capture and activation processes)
  - Generate false vetos in CRV… if rate high enough becomes a source of significant dead-time
  - Cause radiation damage to the read-out electronics (esp. SiPMs)

Mu2e Neutron Shielding



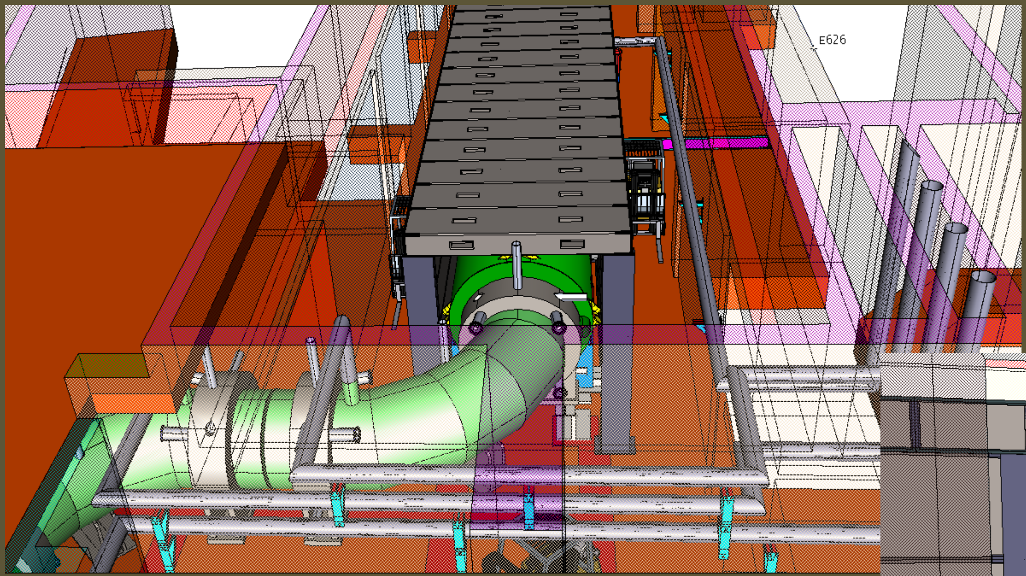
- Have identified a cost effective shielding solution
- Non-trivial optimization required
- Reduces rates of neutrons and photons at CRV to acceptable level

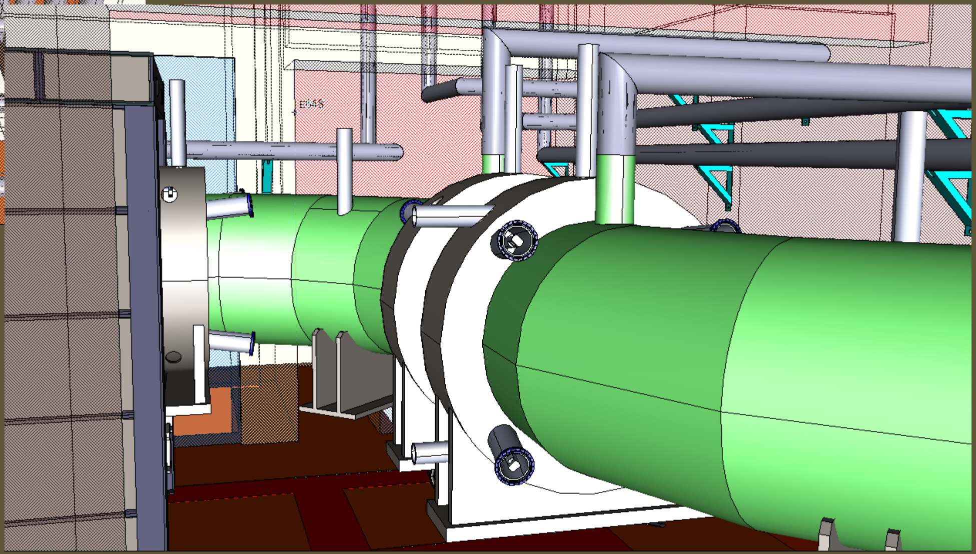
Mu2e Detector Hall

Graphic of proposed Mu2e Detector Hall

- Final Designs completed
  - Scheduled to break ground Fall 2014

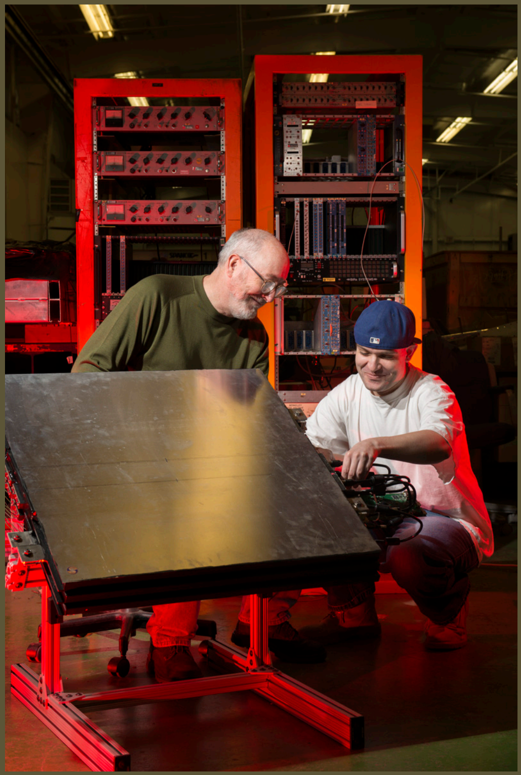
Details, details, details

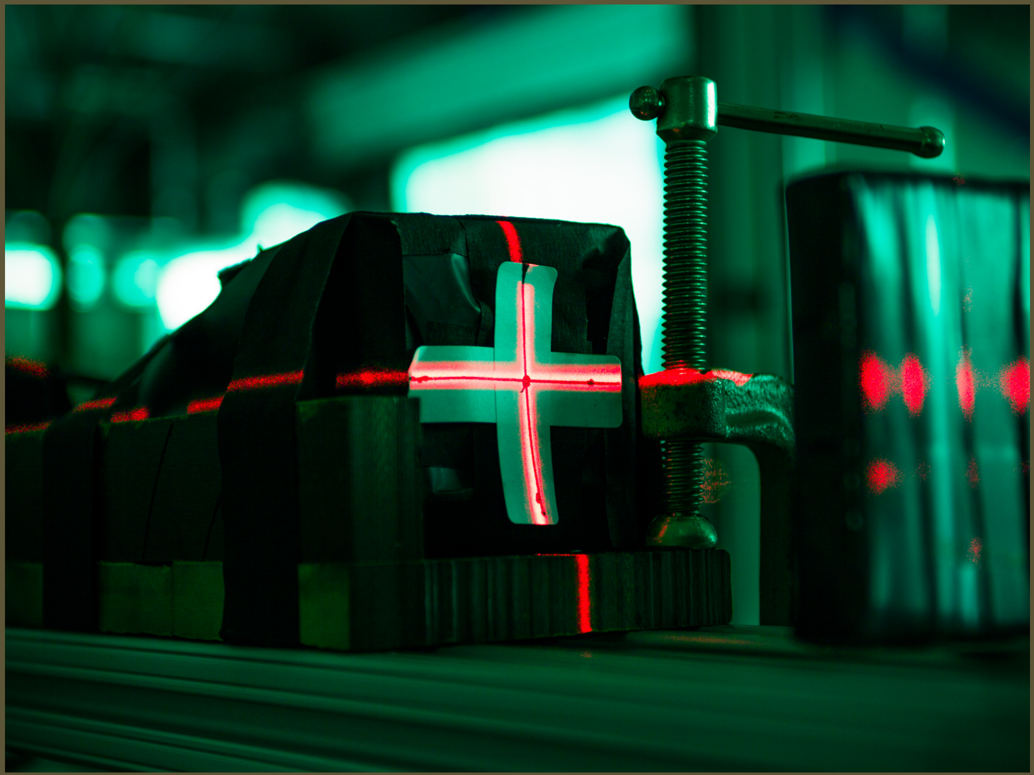




- Working to identify and resolve interface issues

Test Beam – September 2013

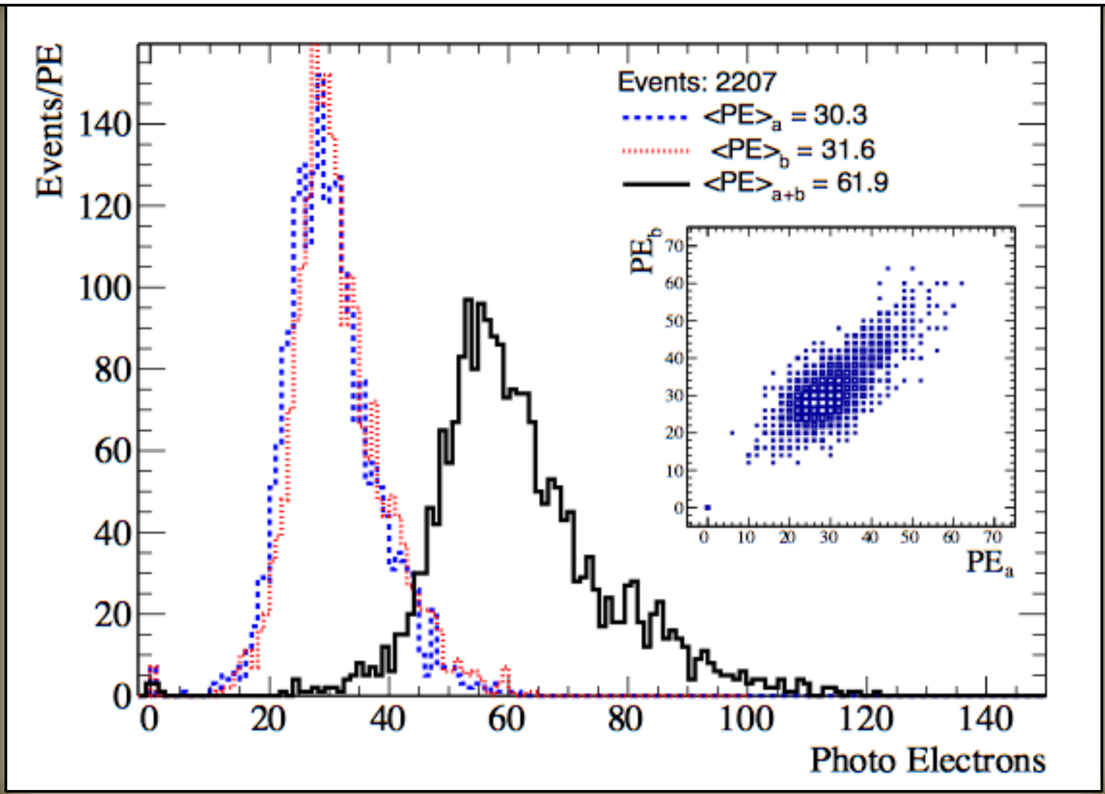




- Cosmic Ray Veto – SiPM, WLS, and component prototype tests
- Upstream Extinction Monitor – conceptual demonstration

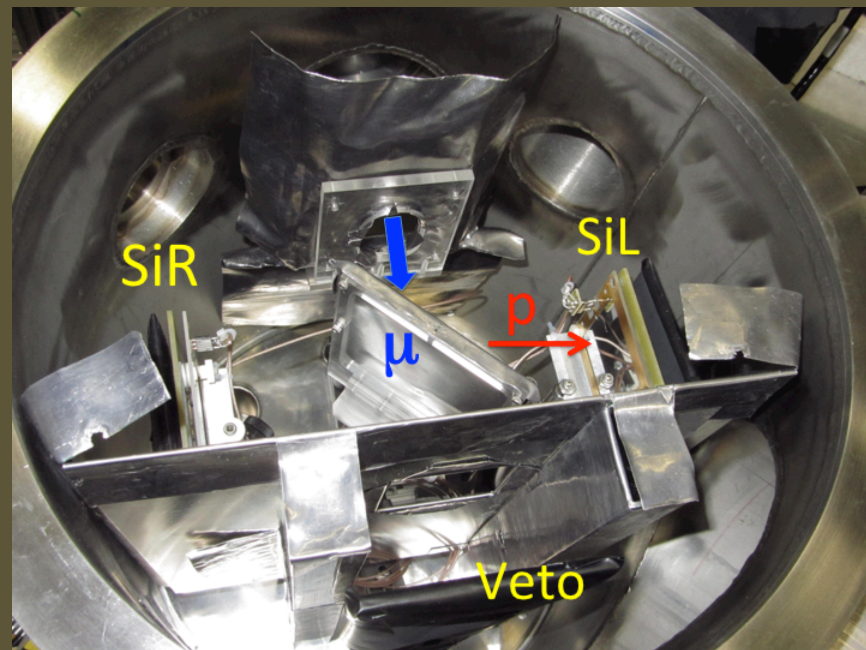
Test Beam – September 2013

Typical light yield from CRV counter prototype – 20 cm from RO end



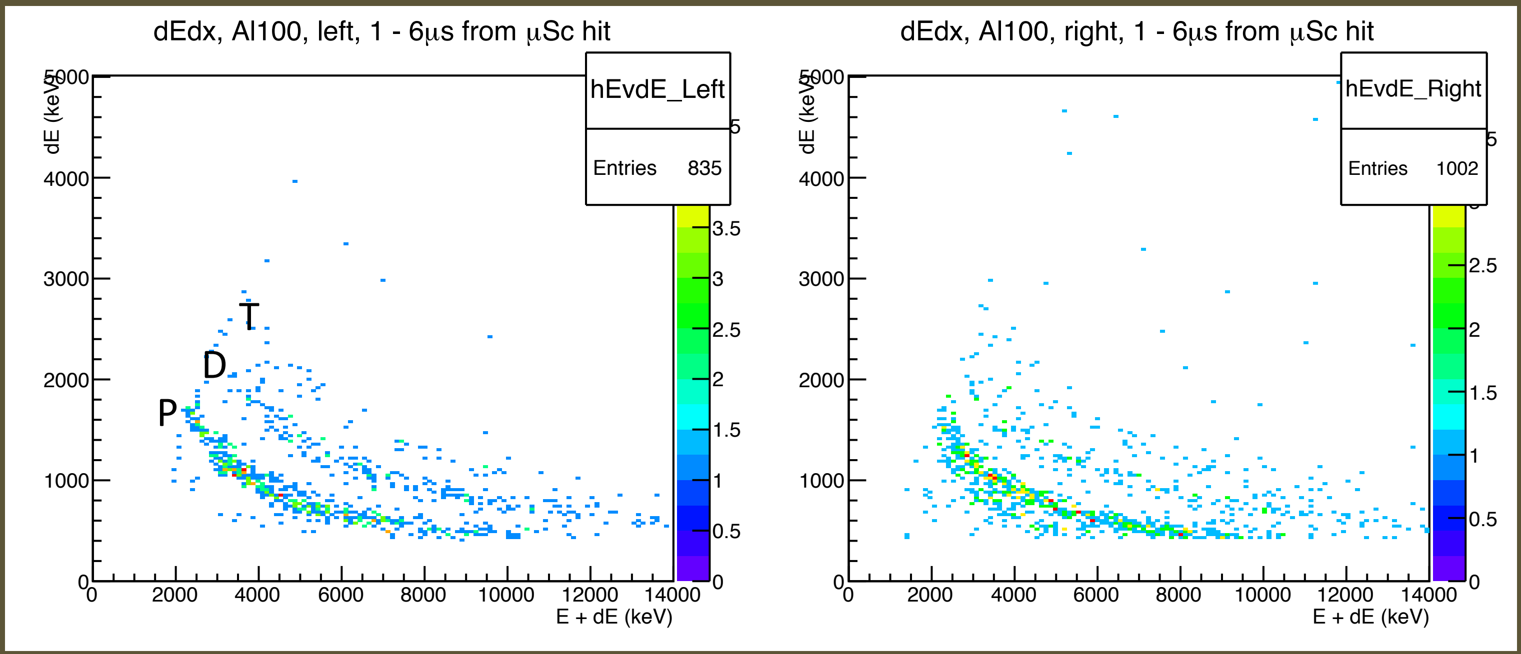
- Achieves veto efficiency >99% at 2.5m from RO
  - want more light to allow for SiPM failure, 10y lifetime
  - will move from 1mm WLS fiber to 1.4 mm

Test Beam – December 2013



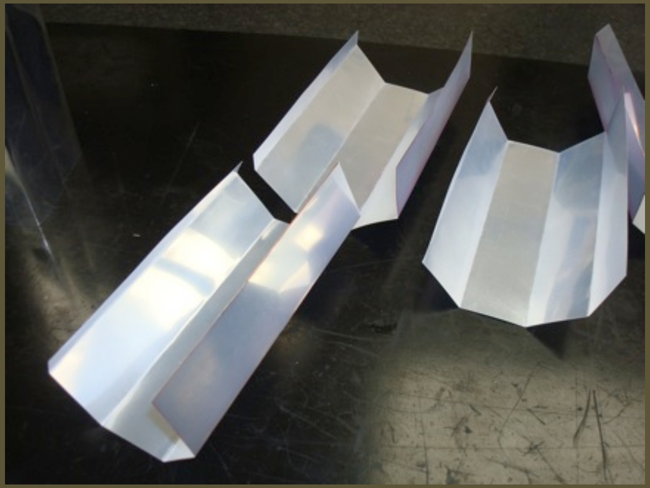
- AlCap – measurement of products of muon captures on aluminum
  - Joint Mu2e/COMET effort
  - Took data at PSI 26Nov – 23Dec

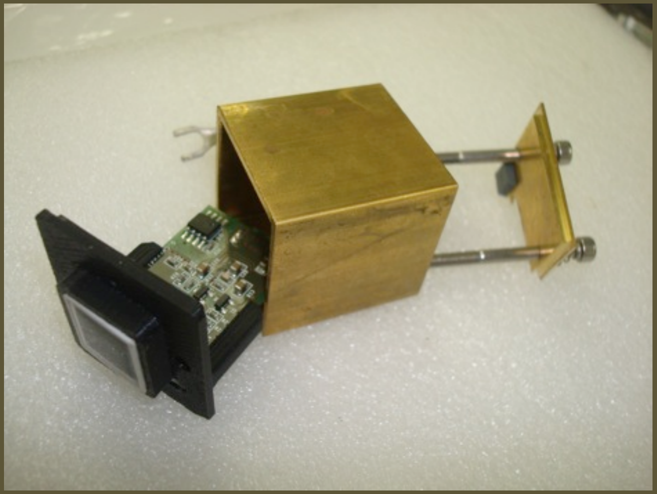
Test Beam – December 2013

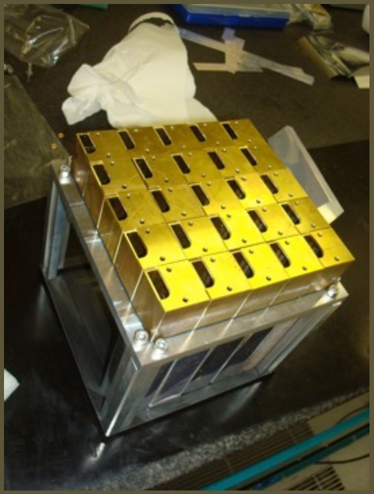


- Preliminary AlCap results
  - Analysis ongoing, but proton, deuteron lines clear

Test Beam Preparations - 2014

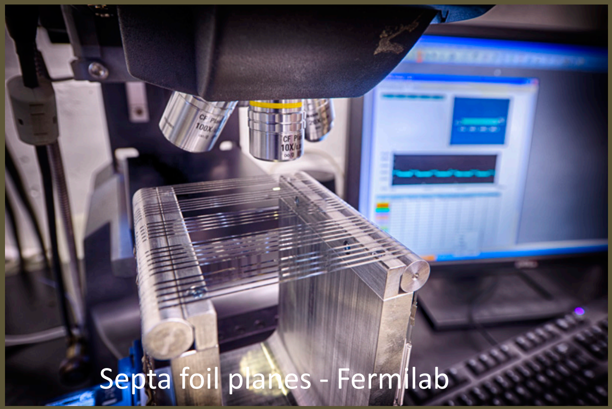




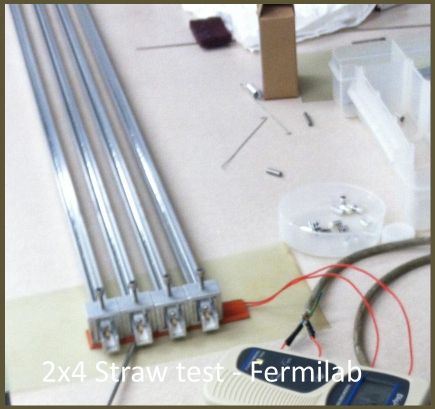


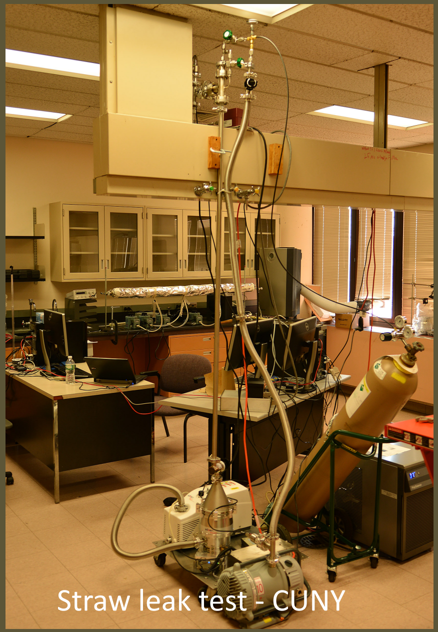
- Test beam (5 -500 MeV e-) in Frascati

Other Mu2e R&D


Septa foil planes - Fermilab


CRV Manifolds – U.Virginia

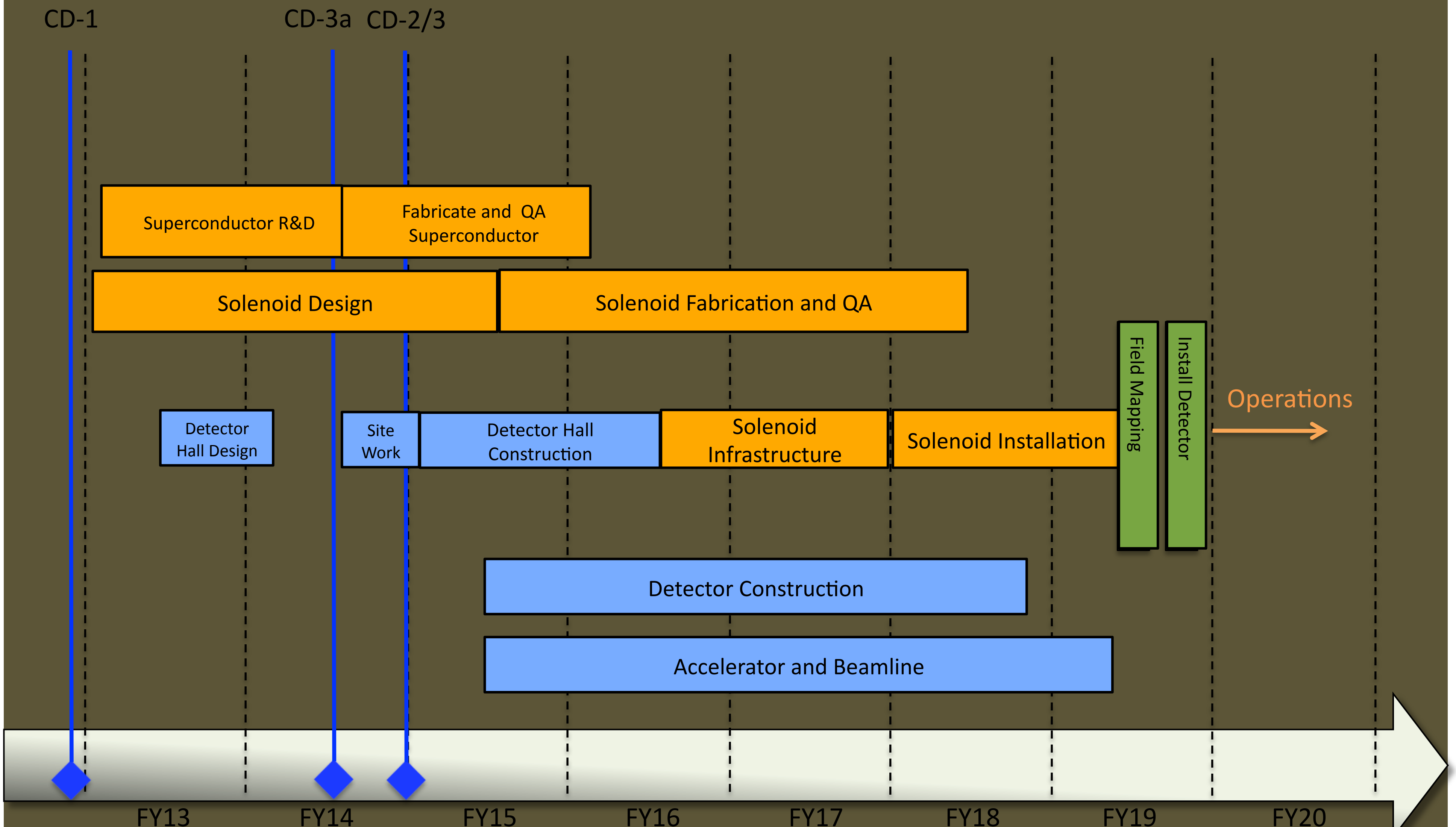

2x4 Straw test - Fermilab


Straw leak test - CUNY

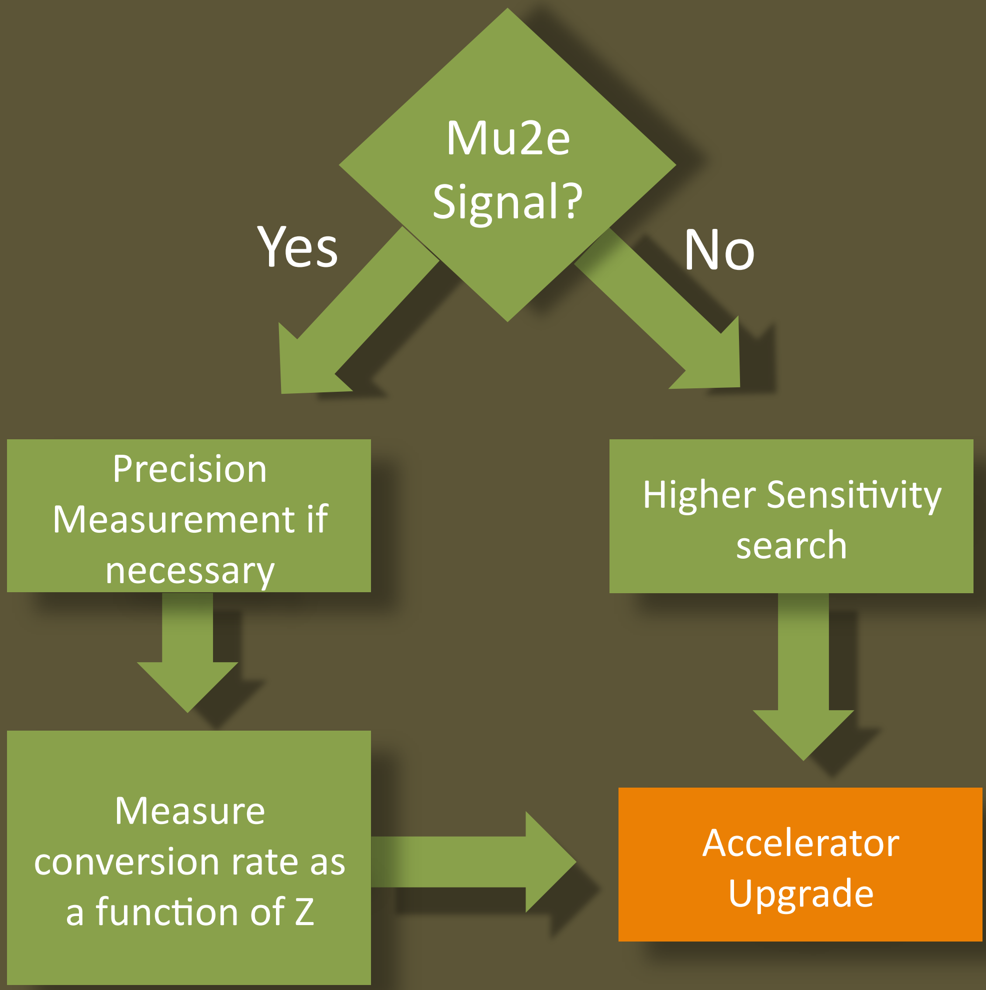
Custom pulsed power supply for fatigue tests on prototype production target - RAL

- Active R&D campaign across project

Mu2e Schedule



What next?

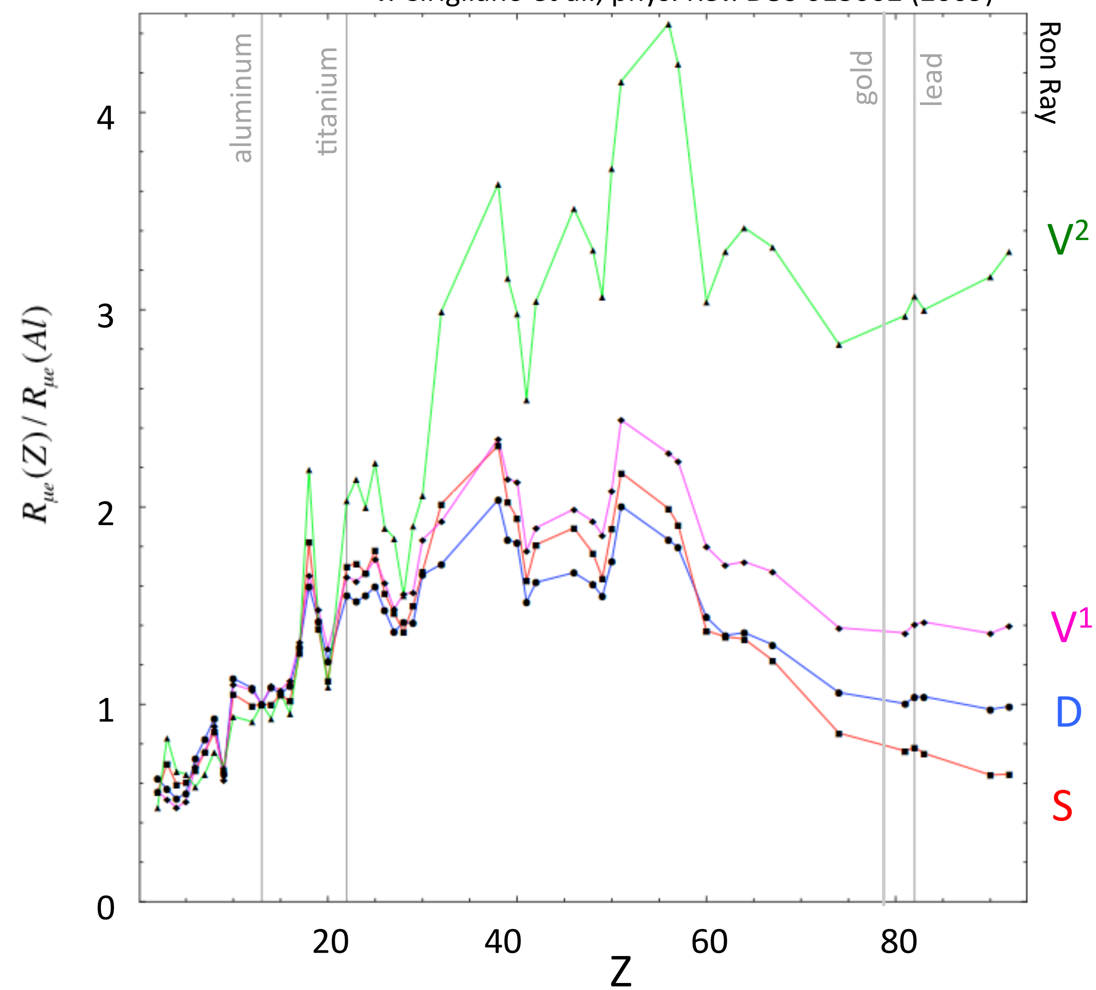


- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator

$\mu N \rightarrow eN$ vs stopping-target Z

- By measuring the ratio of rates using different stopping targets Mu2e can unveil underlying new-physics mechanism

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



Concluding remarks

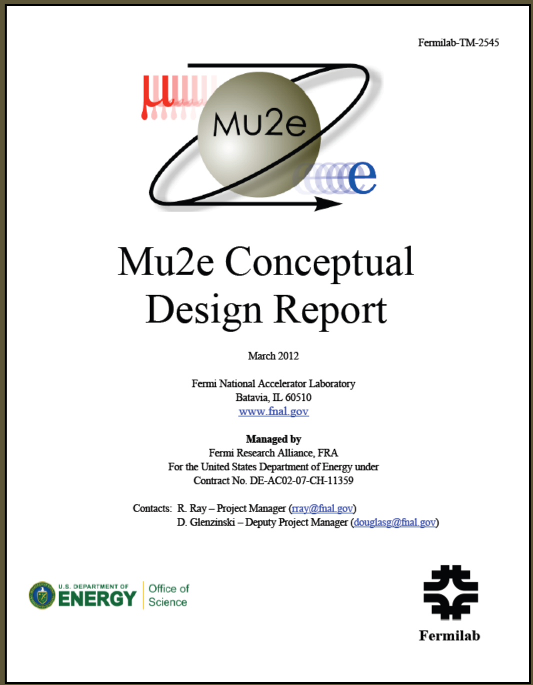
Summary

The Mu2e experiment:

- Improves sensitivity by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- Is complementary to LHC, heavy-flavor, and neutrino experiments
- Will break ground in 2014

Interested in learning more?

- Conceptual Design Report
  – http://arXiv.org/abs/1211.7019



Fermilab-TM-2545

Mu2e

Mu2e Conceptual Design Report

March 2012

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

Contacts: R. Ray – Project Manager (rray@fnal.gov)
D. Glenzinski – Deputy Project Manager (douglasg@fnal.gov)

U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

- Experiment web site
  – http://mu2e.fnal.gov

The Mu2e Collaboration

Mu2e Collaboration, November 2013

- ~130 People, 26 Institutions, 3 Countries

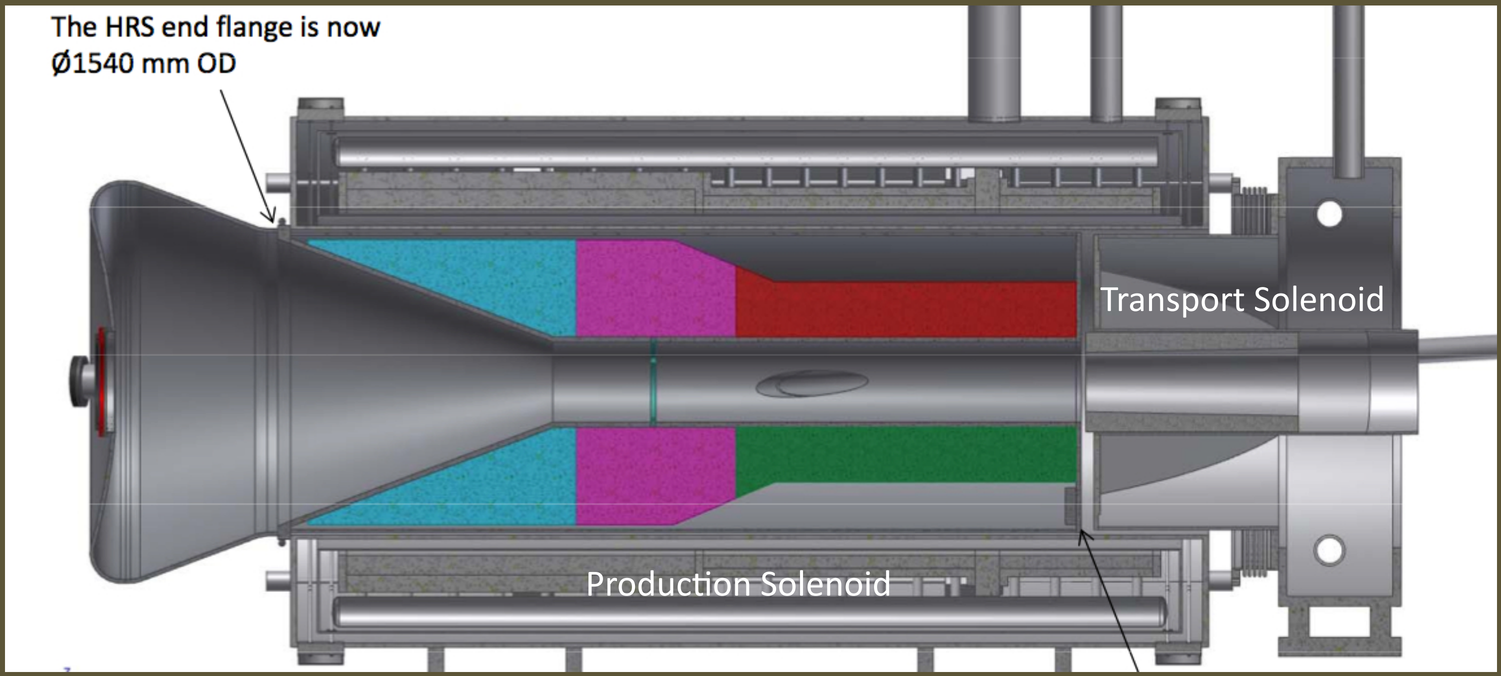
JINR Contributions

- Calorimeter and Cosmic-Ray-Veto Systems
  - Simulation studies
  - Crystal and scintillator testing
  - Neutron and radiation-hardness tests
  - Prototype beam tests
  - Fabrication and commissioning
  - Maintenance, operation, and calibration

JINR Contributions

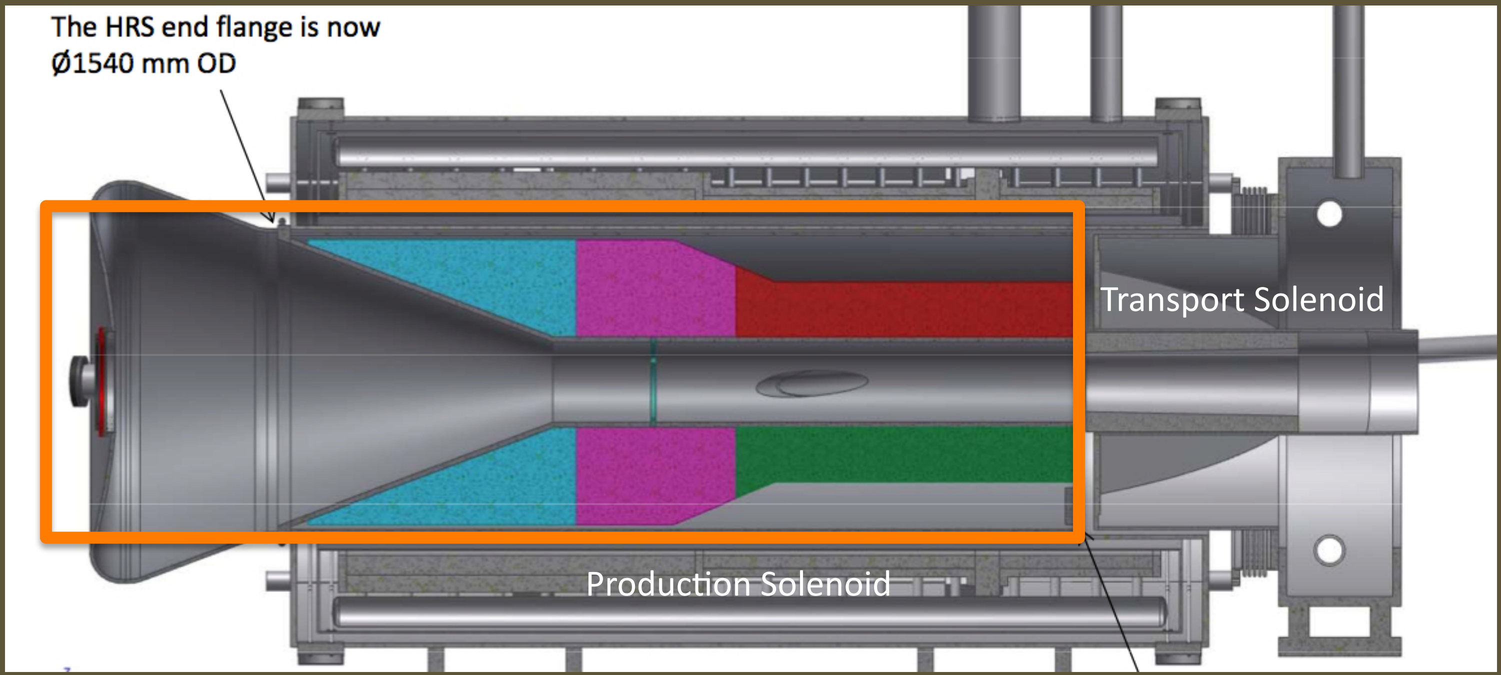
- Production Solenoid Heat and Radiation Shield
  - Discussing significant JINR role in fabrication of HRS (40 tons)
  - Potential role in assembly and testing (non-trivial)
  - Potential role in installation
  - NB. the HRS is important to the success of Mu2e… without it the PS will fail
- Data-taking shifts, data validation, analysis

PS Heat and Radiation Shield



- Must protect production solenoid from heat and radiation deposits from proton beam

PS Heat and Radiation Shield



- Must protect production solenoid from heat and radiation deposits from proton beam

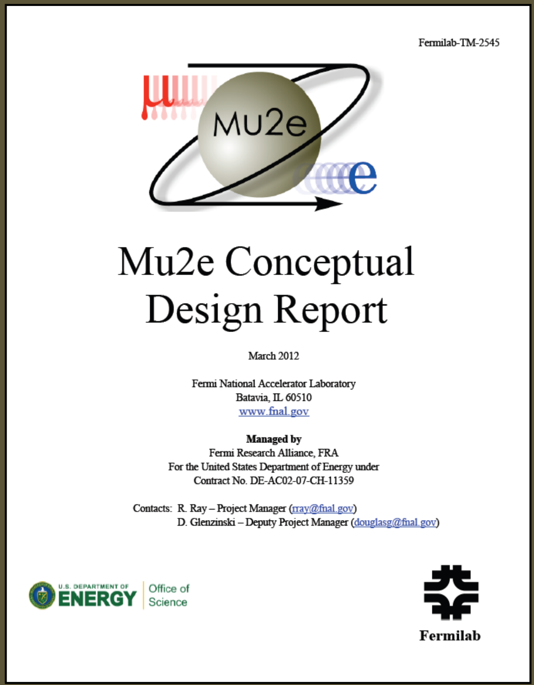
JINR/Mu2e Agreements

- Memorandum of Understanding JINR-FNAL
  - Mu2e, muon (g-2)
  - 2013-2018
- Implementation Agreement JINR-FNAL
  - Mu2e
  - 2013-2016
- Implementation Agreement JINR-INFN
  - Mu2e
  - 2013-2016

Thank You!

- Mu2e Conceptual Design Report
  - http://arXiv.org/abs/1211.7019

- Mu2e Experiment web site
  - http://mu2e.fnal.gov



Fermilab-TM-2545

Mu2e Conceptual Design Report

March 2012

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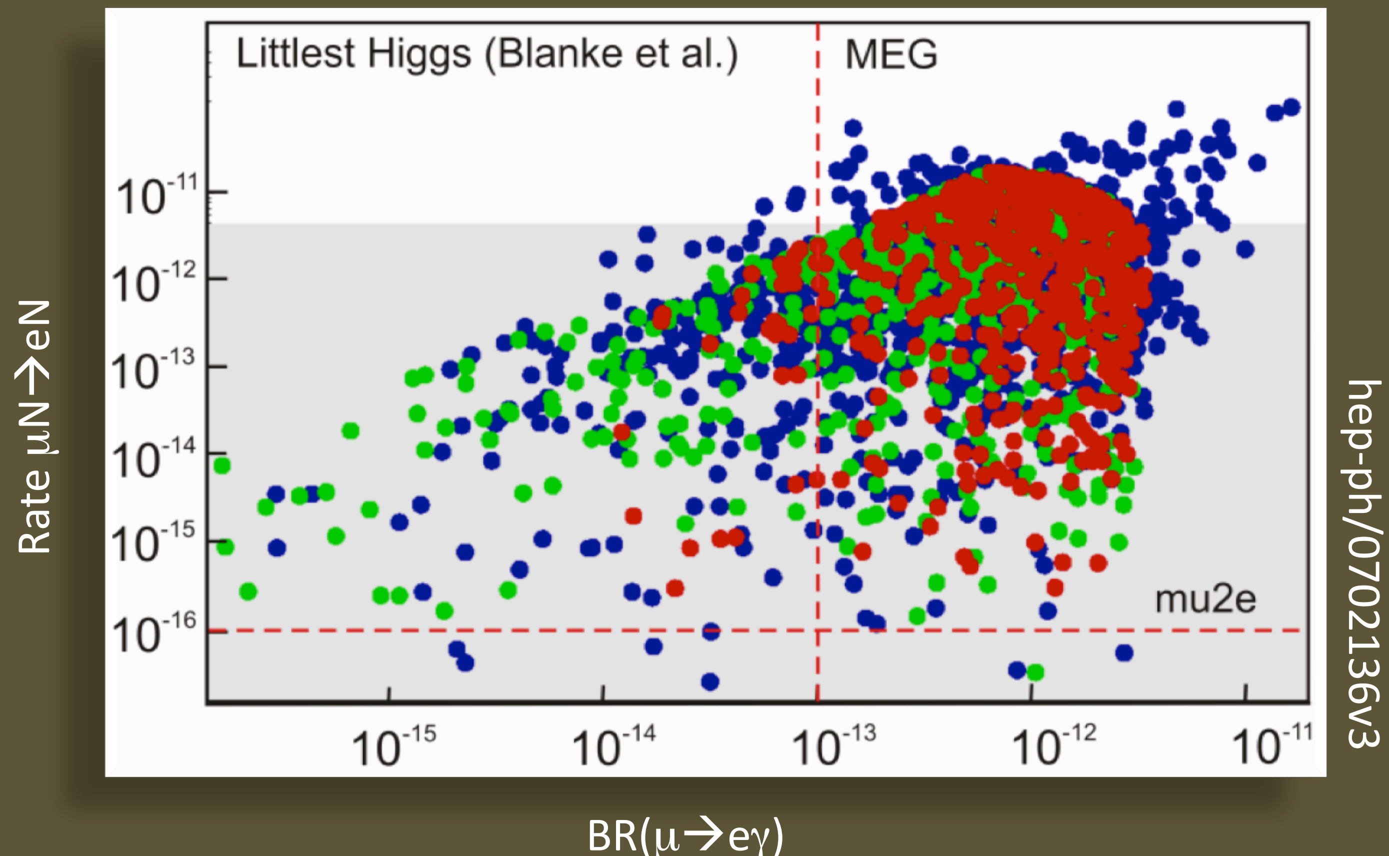
U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

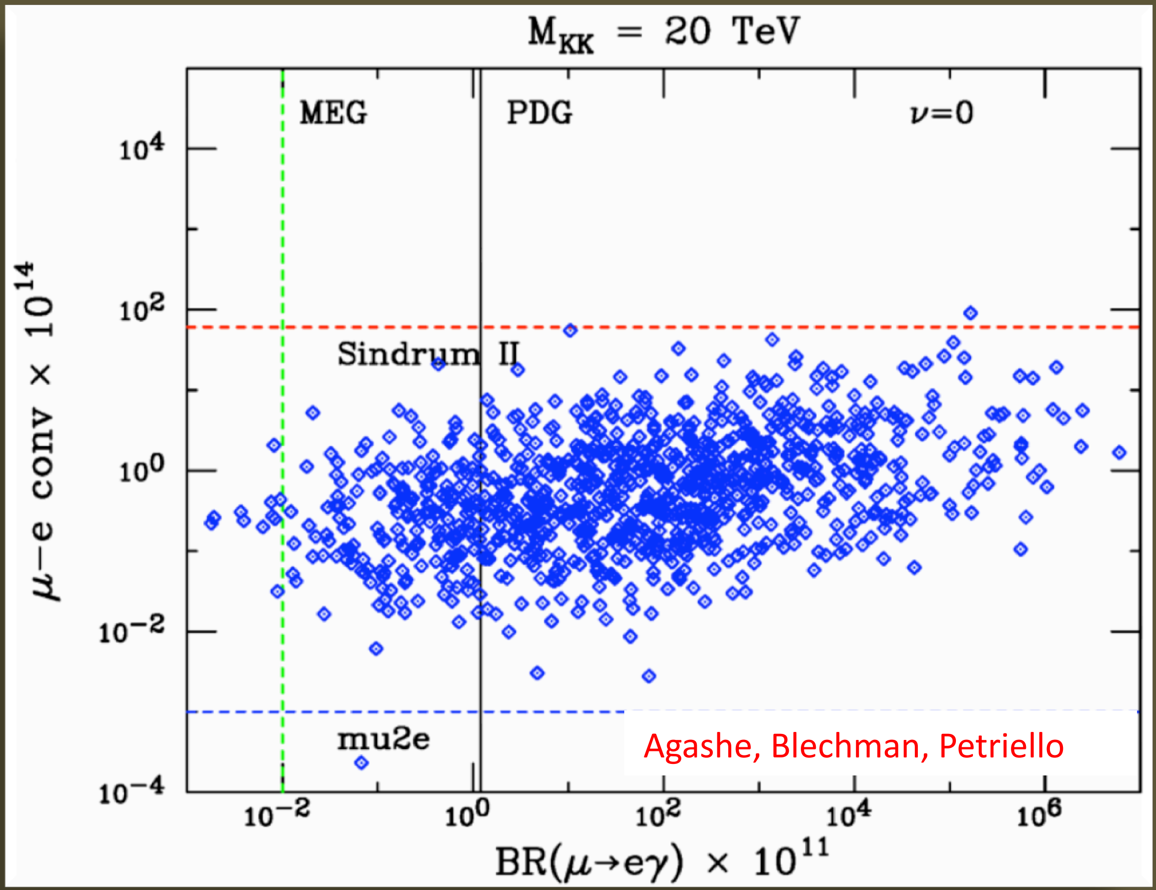
Additional Slides

Mu2e Sensitivity



- Mu2e will cover the entire space

Mu2e Sensitivity

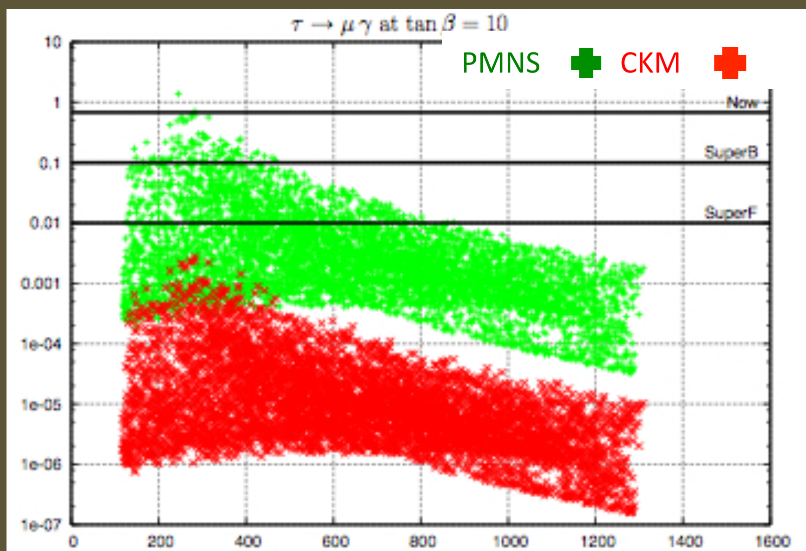


hep-ph/0606021v2

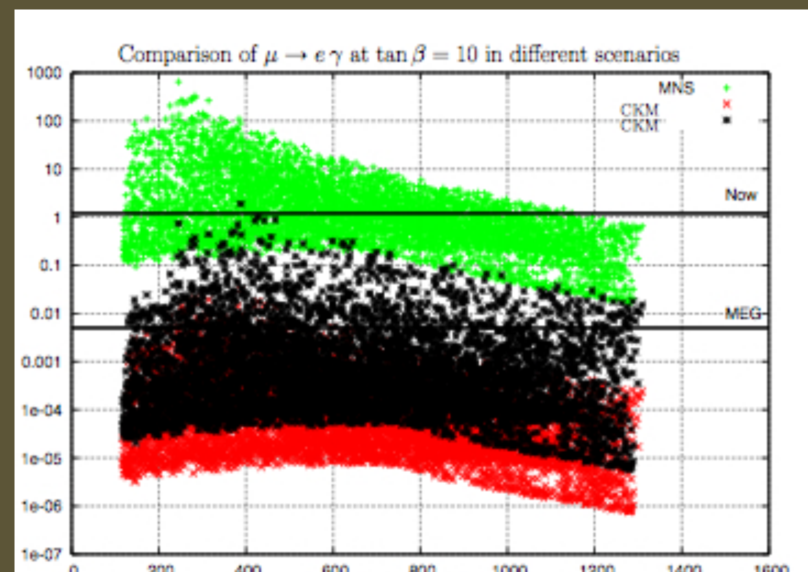
- Mu2e, MEG will each cover entire space

Mu2e Sensitivity

BR(τ→μγ) / 10^{-7}



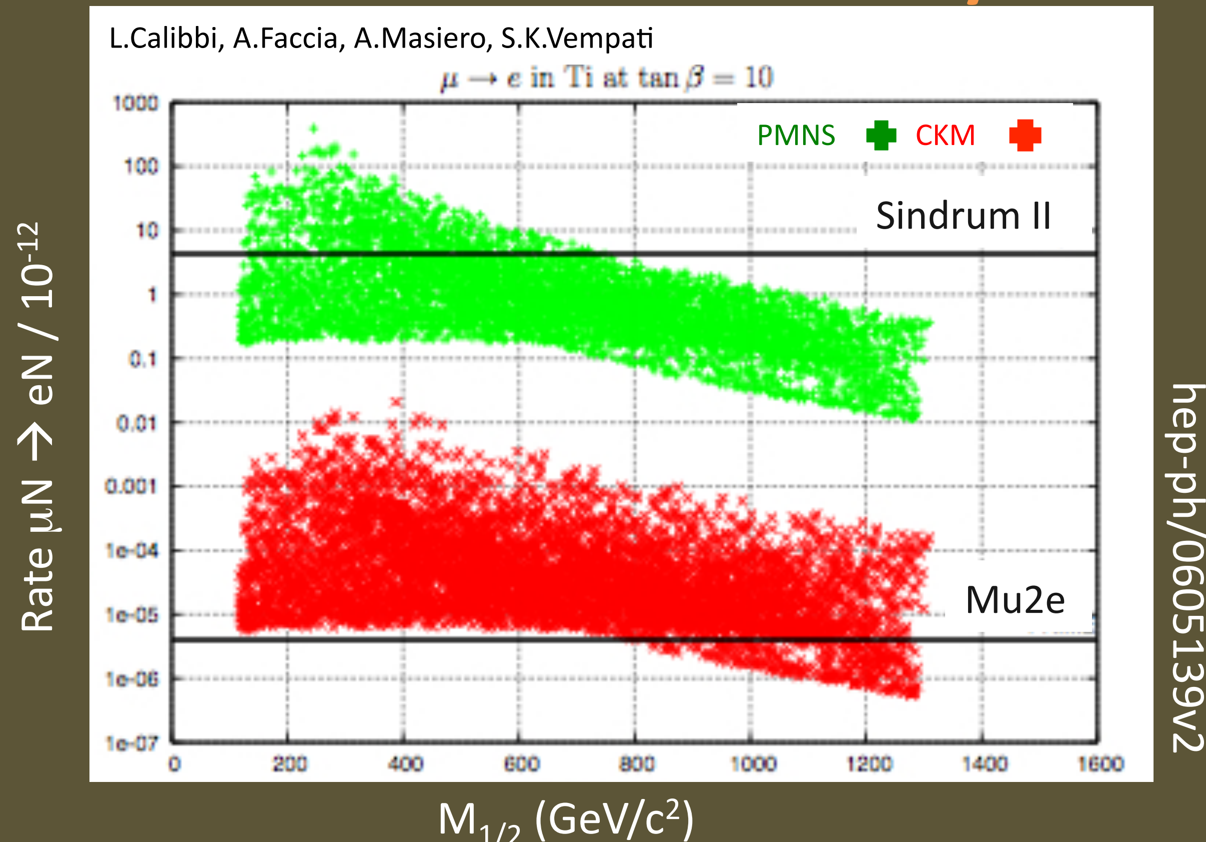
BR(μ→eγ) / 10^{-11}



$M_{1/2}$ (GeV/c^2)

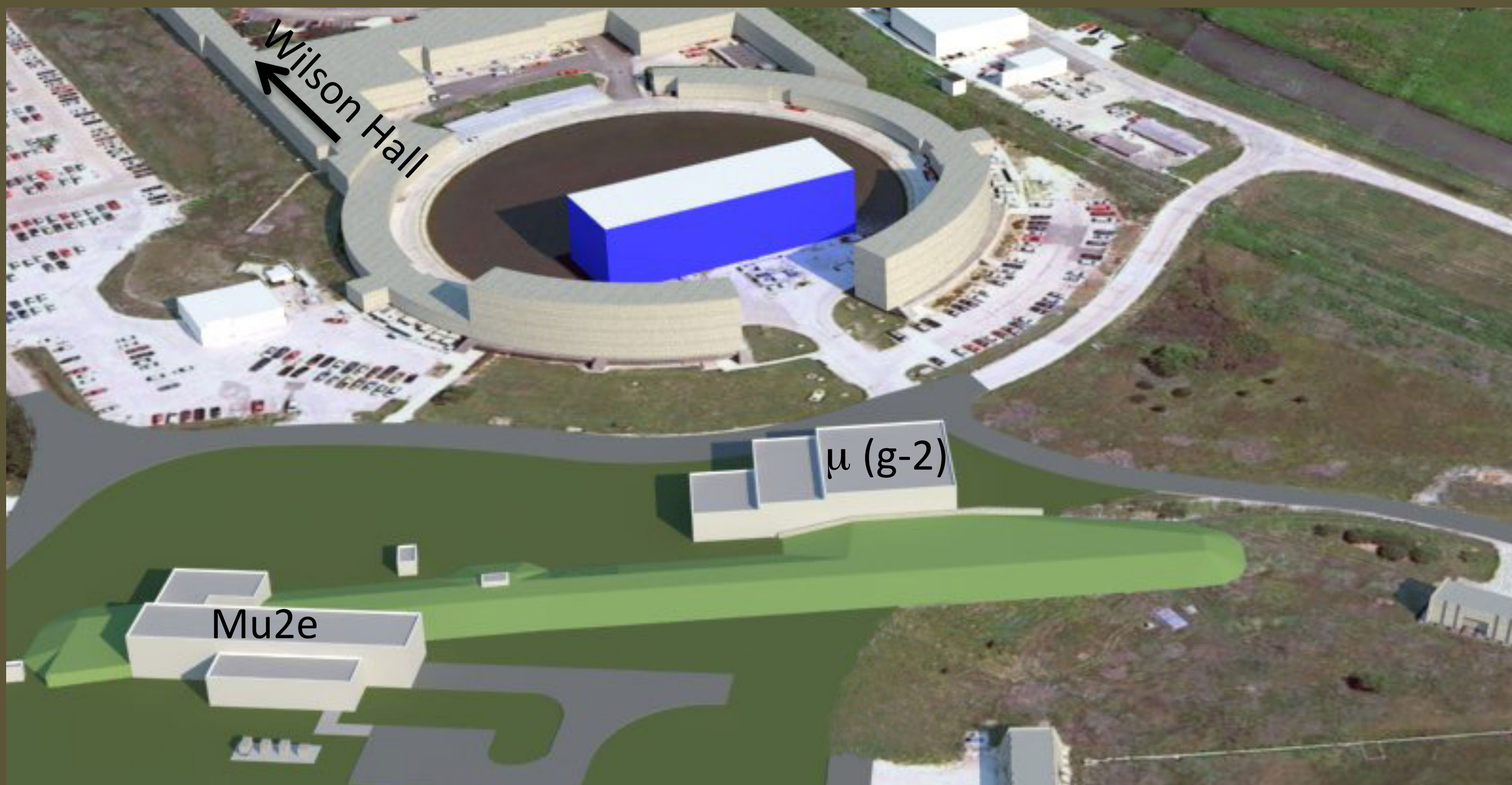
- μ→eγ, τ→μγ will begin to probe this space

Mu2e Sensitivity



- Mu2e will cover (almost) entire space

Mu2e at Fermilab



- Mu2e will be located together with Muon (g-2) just west of Wilson Hall.

Mu2e Proton Timing

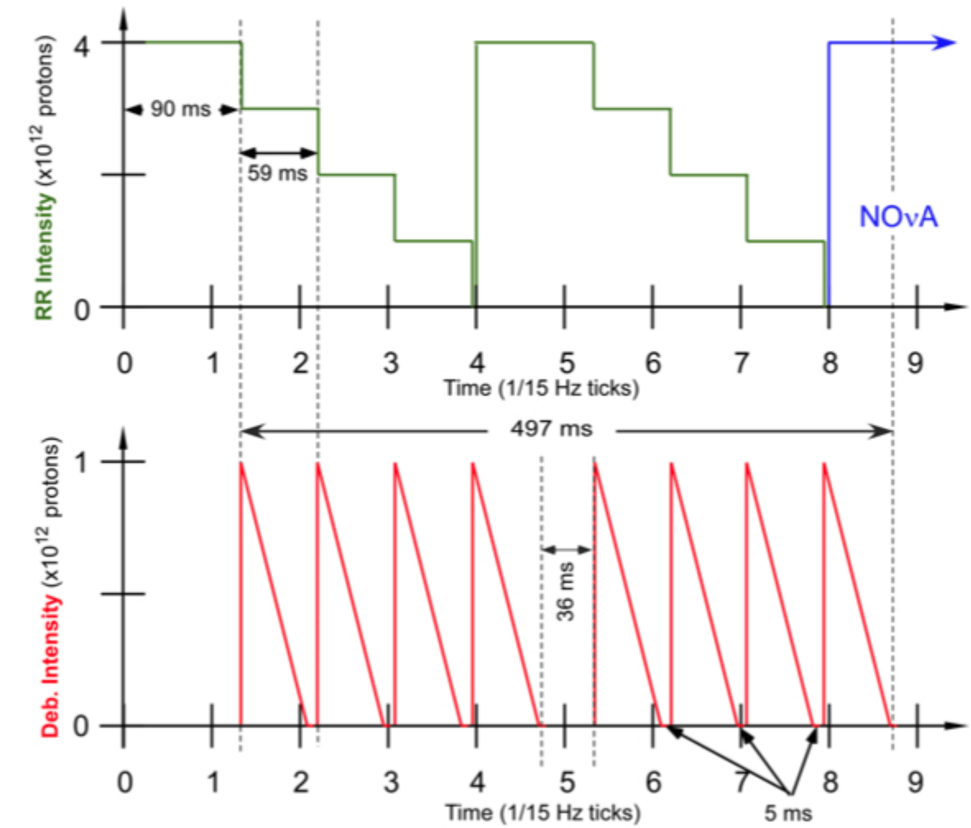
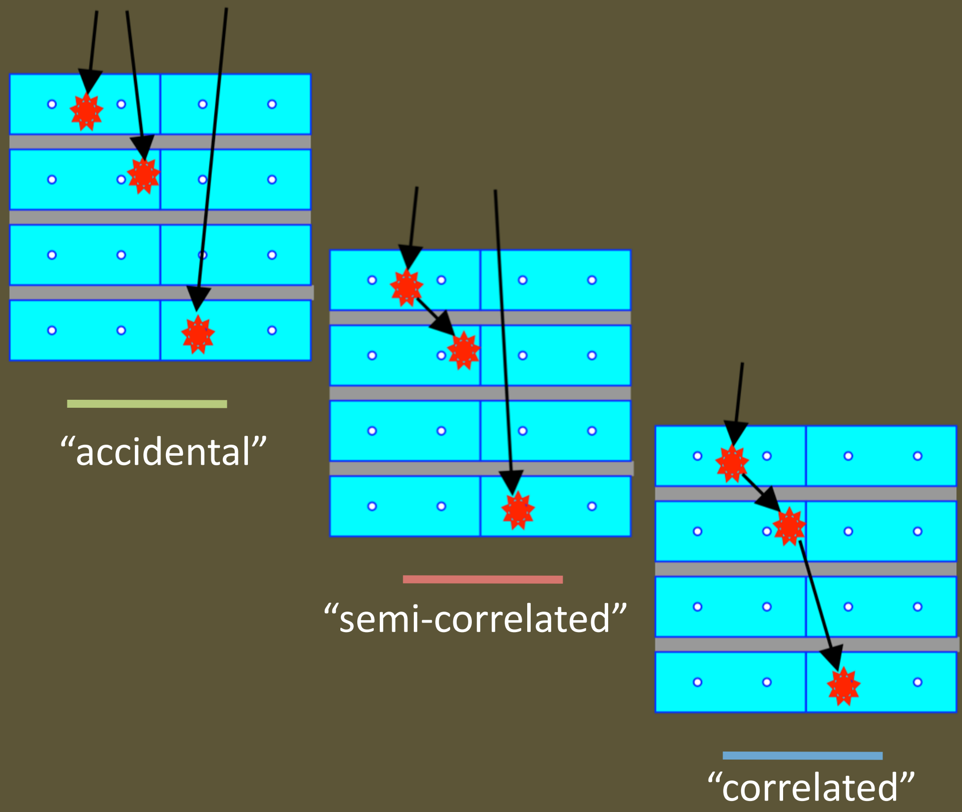
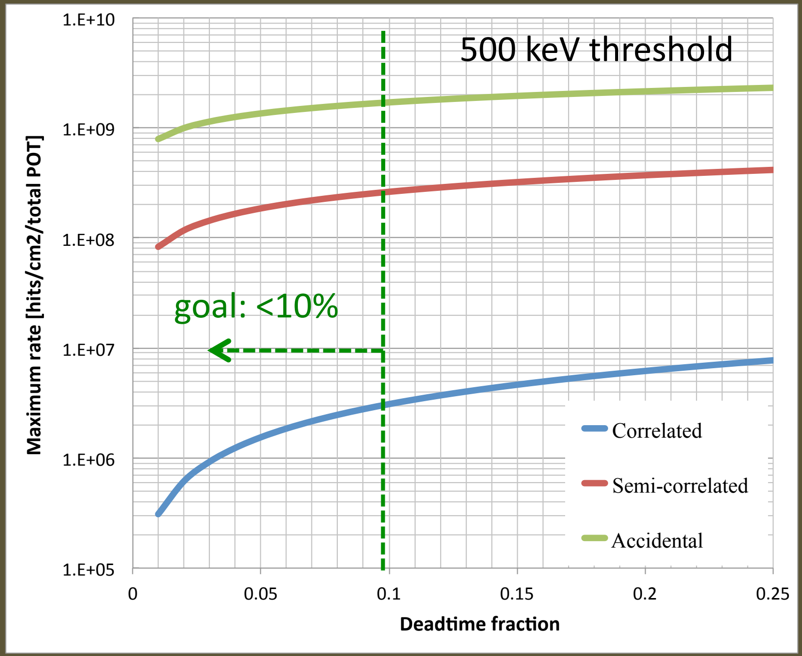


Figure 5.4. This figure shows the first eight Booster ticks of a Main Injector cycle. Proton batches are injected into the Recycler at the beginning of the cycle and again at the fourth tick. After each injection, the beam is bunched with 2.5 MHz RF and extracted one bunch at a time.

- Mu2e will run simultaneously with NOvA

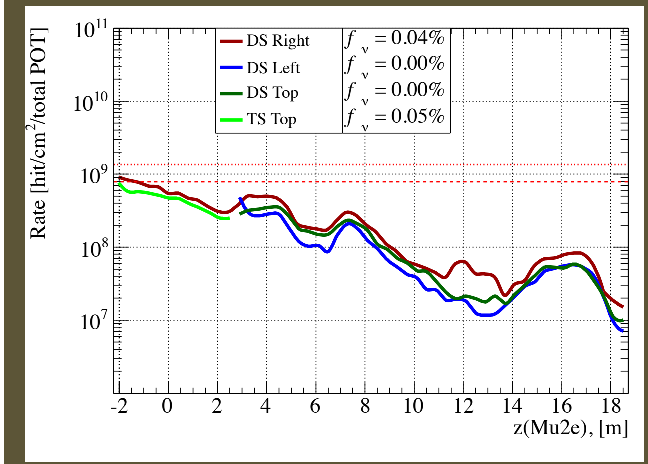
Mu2e Neutron Shielding



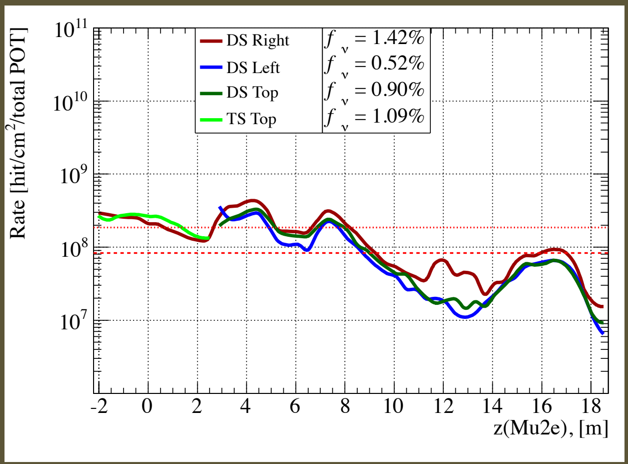


- We needed to understand contributions from accidentals and correlated-accidentals
  - For neutrons and photons as a function of time, energy, timing resolution, and read-out threshold

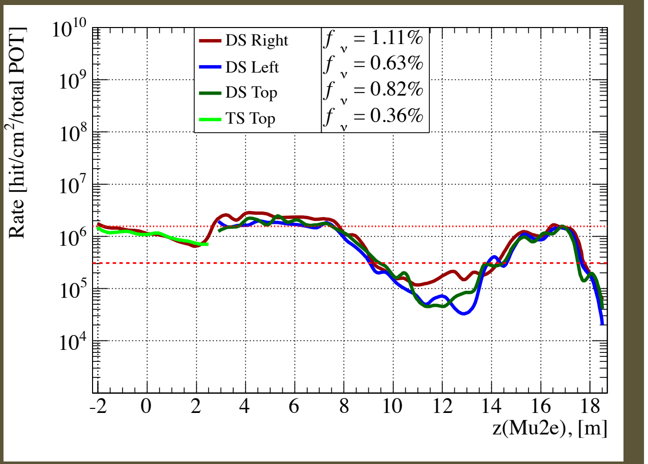
Mu2e Recent Progress: Shielding Designs



accidental



semi-correlated



correlated

- Total dead time from neutron/photon "noise" = 8%
  - For 500 keV readout threshold
  - Increasing to 1 MeV reduces to 2%
  - In progress: Cross-check with a separate physics generator (MARS)

Epilogue

- High Energy Physics is at a crossroads
  - We know that the Standard Model is incomplete
  - We have lots of ideas about what a more complete model might look like
  - … but we have no idea which is the right one

Epilogue

Fermilab's Mu2e experiment is important because it is designed to discover which direction is the right one

As a function of Z

- Things change